Slipstream Aerospace©

Presents

SWAT©

Strut-braced Wing and T-tail

A response to the 2009/2010 AIAA Foundation Undergraduate Team Aircraft Design Competition

Presented by Virginia Polytechnic Institute and State University

Slipstream Aerospace©

From left to right: Marshall Ebner, Kevin Wulff, David Pfister, Teddy Mbwadzawo, Andy Hsu, Jorge Arias and Ivan Fernandez

Ivan Fernandez
CAD Drawings
AIAA Member # 413633

Douglas Ebner
Systems Analysis
AIAA Member # 274237

Teddy Mbwadzawo
Aerodynamics Analysis
Not AIAA Member

David Pfister
Project Lead, Stability and Control
AIAA Member # 416481

Kevin Wulff
Performance Analysis
AIAA Member # 423779

Dr. William Mason
Project Advisor
AIAA Member # 11141

Jorge Arias
Biofuels and Structures
AIAA Member # 280881

Andy Hsu
Cost, Engine and Weights
AIAA Member # 288016

Dr. Mayuresh Patil
AIAA Advisor
AIAA member # 144995

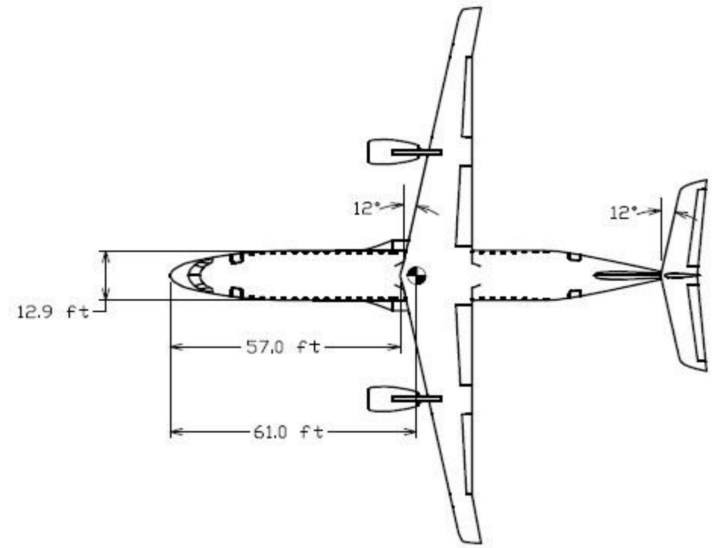
Executive Summary

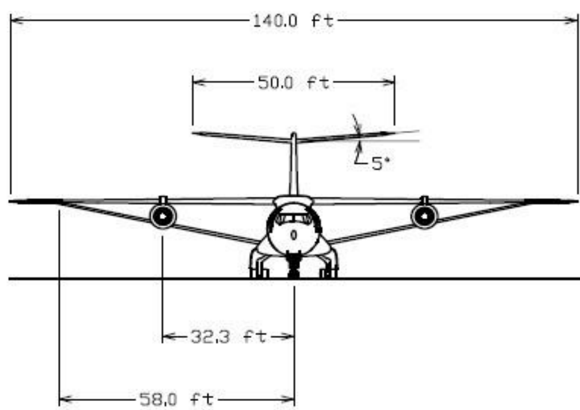
The RFP calls for designing a one-class commercial airliner that can carry a passenger load of 175 passengers. Additionally the aircraft must have a balanced field length below 8200 feet at any airport as well as having a maximum lift to drag ratio 125% of the Boeing 737-800 series. The maximum cruise altitude is to be 41,000 feet and the cruise Mach number is to be 0.8 with a maximum Mach number of 0.83. The target production date is set to 2020, which allows for currently in development *technologies* to be utilized by the designers; in relation to that the aircraft must be capable of utilizing biofuels as an alternative to Jet-A.

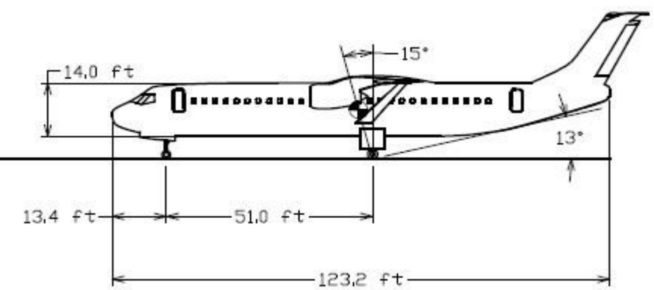
Slipstream Aerospace's response was the SWAT design, the initial hypothesis was to design an aircraft with an increased span to provide the needed lift to drag ratio increase, select a supercritical airfoil specifically designed to operate in the transonic region. Use a strut to brace the wing to allow for a reduced wing weight by thinning the wings. Select an appropriately powerful engine that also allows for the use of biofuels.

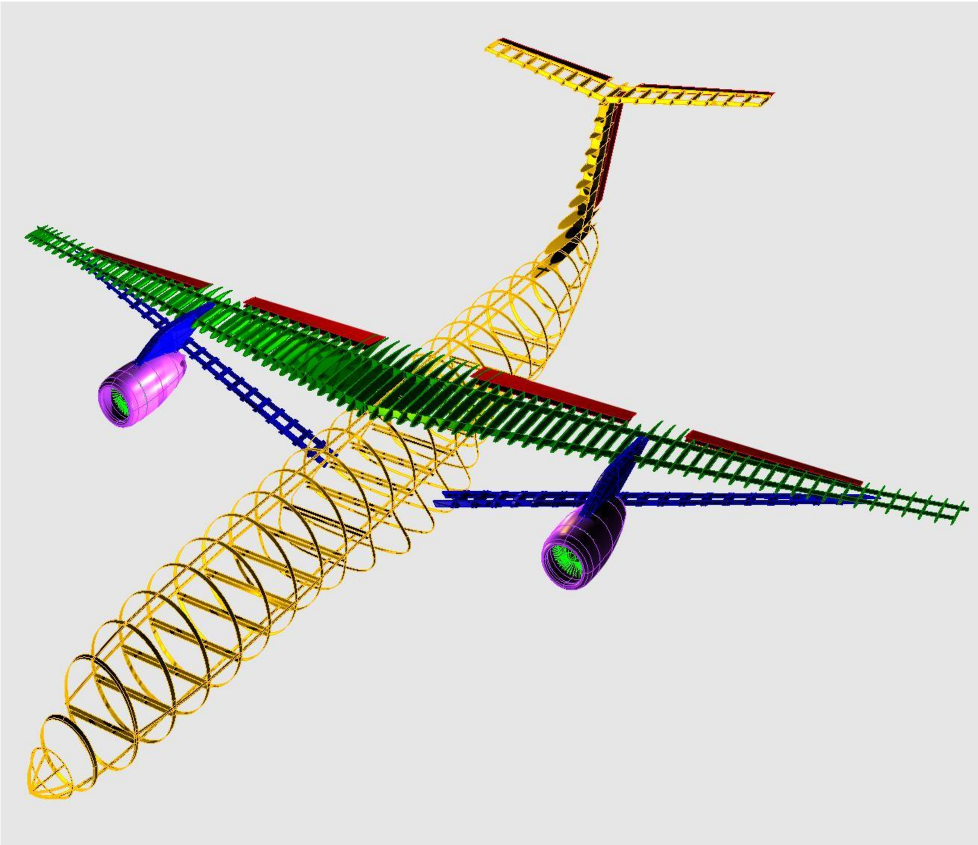
The SWAT design, a Strut-braced Wing And T-tail, it utilizes a high wing and T-tail to prevent turbulent flow from passing over the wings and interfering with the horizontal tail and elevator at low angles of attack. To prevent the high wing second trim point from ever being encountered an angle of attack limiter is utilized. The strut allows for a reduction in weight which leads to improved fuel efficiency. The wing sweep was reduced to promote laminar flow and reduce drag. The wings were extended to a wing span of 140 feet to allow for the required improvement in the lift to drag ratio. The NASA SC(2)-0610 was chosen for the main wing and horizontal tail airfoils due to its performance in the transonic region as well as Korn equation results. Slipstream Aerospace is confident that this design not only meets and exceeds the requirements of the RFP, but also that it is a good fit for the average traveler.

	Units	Wing	Horizontal Tail	Vertical Tail
Area	ft^2			
Reference	ft^2	1454.9	375	245.5
Whetted	ft^2	2968	765	502.8
Span	ft	140	50	23
Aspect Ratio	-	13.52	6.667	2.155
Taper Ratio	-	0.284	0.667	0.692
Thickness-to-Chord Ratio	-	0.1	0.1	0.12
Chord Length	ft			
Root	ft	17.63	9	13
Tip	ft	5	6	9
MAC	ft	12.5	7.6	11.12
1/4 Chord Sweep	degrees	9.37	10.09	27.93
Dihedral	degrees	-	5	-









Material	Color
Carbon fiber reinforced polymer	Dark Green
Aluminum 2024-TO and heating mats	Red
Titanium Alloy AMS 4914	Dark Blue
Fiber Metal Laminate	Magenta
Aluminum 2024-TO	Yellow
Aluminum 2024-TO	Yellow
Aluminum Titanium Alloy Ti6Al4V	Light Green

Figure 0.1 - Structural Layout and Materials

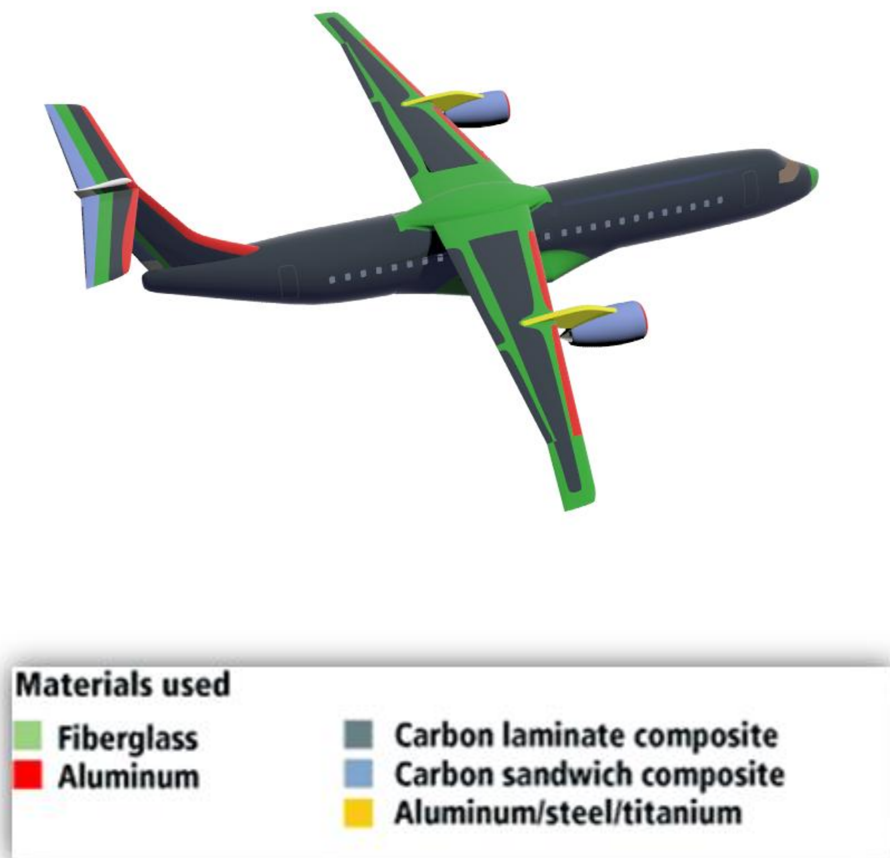


Figure 0.2 – Skin Materials

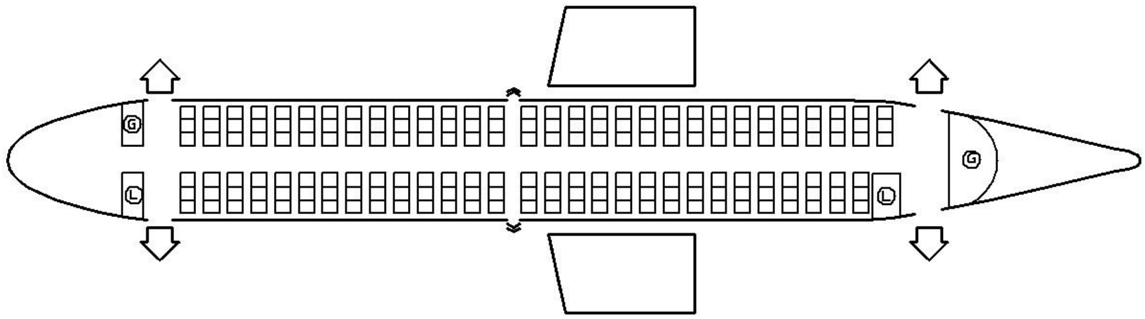


Figure 0.3 – Seating Layout

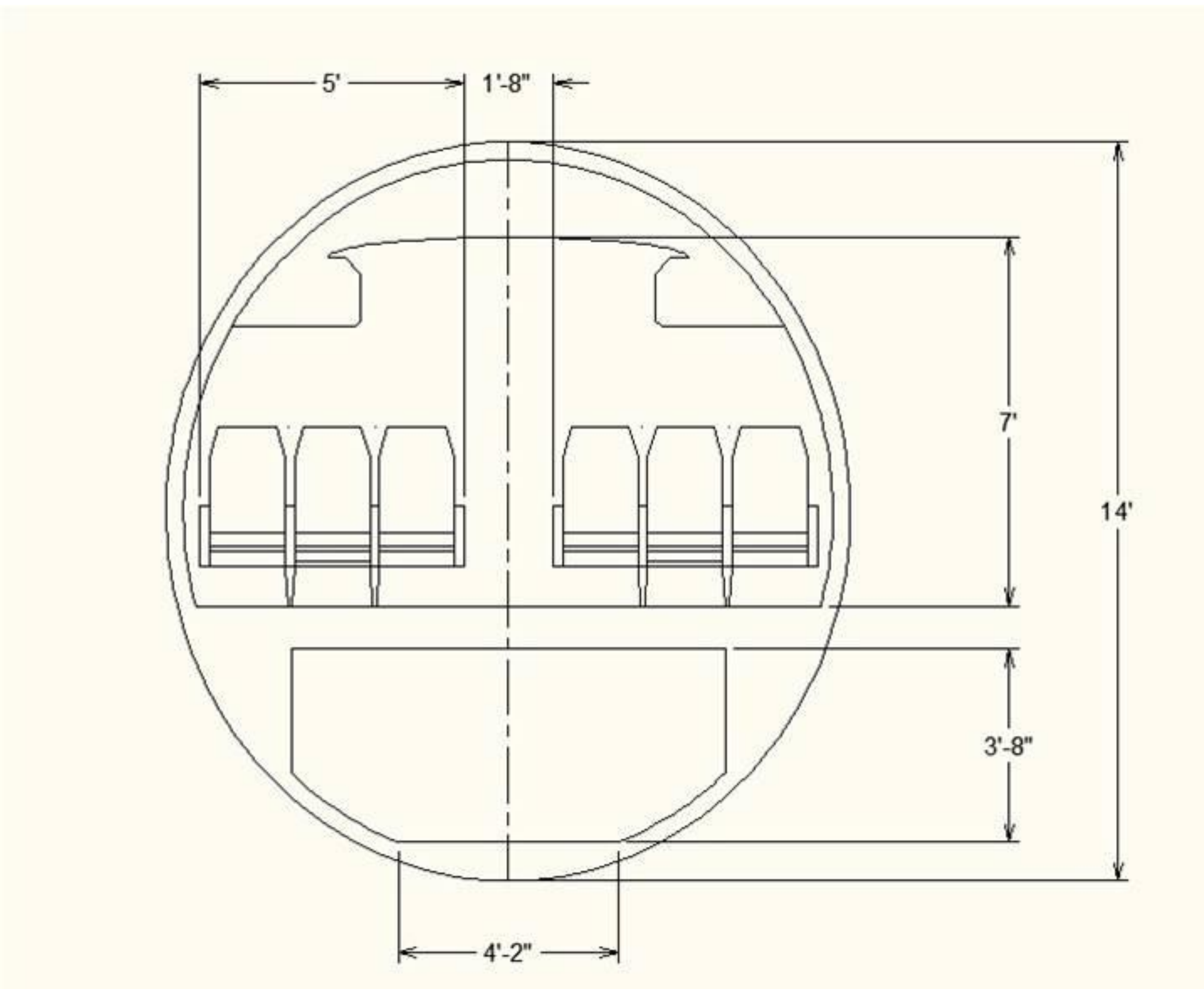


Figure 0.4 – Interior Dimensions

Table of Contents:

Nomenclature

Symbol	Definition	Units
A	Aspect Ratio	-
A_{side}	Side View Area	ft^2
A_{top}	Top View Area	ft^2
b	Wingspan	ft
C	Specific Fuel Consumption	$\frac{lb}{lbf * hr}$
C_{D0}	Zero Lift Drag Coefficient	-
C_{fe}	Skin Friction Coefficient	-
C_{LB}	Life Coefficient due to Sideslip	-
$C_{L_{max}}$	Maximum Lift Coefficient	-
C_{Lp}	Lift Coefficient due to Pitch	-
C_{Lr}	Lift Coefficient due to Rudder	-
$C_{L_{MaxTO}}$	Maximum Lift Coefficient at Take off	-
$C_{L_{TO}}$	Lift Coefficient at Take off	-
C_{Navail}	Available Yaw Moment Coefficient	-
C_{NB}	Yawing Coefficient due to Sideslip	-
C_{Np}	Yawing Coefficient due to Pitch	-
C_{Nr}	Yawing Coefficient due to Rudder	-
C_{Nreq}	Required Yaw Moment Coefficient	-
C_xH_y	Generic Hydrocarbon Fuel Where y=2x+2	-
CO_2	Carbon Dioxide Molecule	-
C_{yB}	Side Force Gradient due to Sideslip	-
C_{Yr}	Side Force Gradient due to Rudder	-
D	Drag	lb
e	Oswald Efficiency Factor	-
H_2O	Water molecule	-
K	Induced Drag Factor	-

K_{vs}	Variable Sweep Constant	-
L	Lift	lb
M	Bending Moment	lb-in
M_{max}	Maximum Mach number	-
M2	Reaction moment at the wing root	lb-in
n	Aircraft Load Factor	g's
O_2	Oxygen gas molecule	-
q	Dynamic Pressure	psf
R	Range	nm
R2	Reaction Force at the Wing Root	lb
S	Wing Planform Area	ft^2
S_{wet}	Wetted Area	ft^2
S_{ref}	Reference Area	ft^2
T	Thrust	lbf
TOP	Takeoff Parameter	-
$\frac{T}{W}$	Thrust to Weight Ratio	$\frac{lbf}{lbs}$
V	Velocity	$\frac{ft}{sec}$
V (Structures)	Shear force	lbf
V_{stall}	Stall Velocity	$\frac{ft}{sec}$
V_{TO}	Takeoff Velocity	$\frac{ft}{sec}$
W	Weight	lbs
W_{fi}	Weight of Fuel at Segment 'i'	lbs
W_0	Takeoff Ground Weight	lbs
$\frac{W_i}{W_{i-1}}$	Weight Ratio of Mission Segment	-
$\frac{W_e}{W_0}$	Empty Weight Fraction	-
$\frac{W}{S}$	Weight to Area ratio	$\frac{lb}{ft^2}$
β	Sideslip Angle	°
δ_a	Aileron Deflection Angle	°
δ_r	Rudder Deflection Angle	°
ζ_{PH}	Phugoid Damping Ratio	-
ζ_{SP}	Short Period Damping Ratio	-

ρ	Density at an Altitude	$\frac{Slugs}{ft^3}$
ρ_{sL}	Density at Sea Level	$\frac{Slugs}{ft^3}$
ρ_{TO}	Density at Takeoff	$\frac{Slugs}{ft^3}$
σ	Density Ratio	-
φ	Bank Angle	°
ω_{sp}	Short Period Natural Frequency	-

List of Figures

List of Tables

1 Introduction and Request for Proposal

1.1 Introduction

On May 14, 1907 the first flight with a passenger was performed on one of the Wright Brothers flyers that had been modified to include a seat for passengers. Since that flight the field of commercial airliners has evolved into what it is today. The requirements since then have also evolved to include substantially increased range, passenger count, speed, fuel efficiency, safety and passenger comfort.

Considering the environmental impact of carbon emissions it is time for a change in fuel type as well as increased fuel efficiency. As companies compete to fill this need for change by offering different types of biofuels and designs for higher lift/lower drag aircraft, several possibilities exist for which direction the future may take.

1.2 RFP Analysis

The request for proposal for the 2009-2010 AIAA Foundation Undergraduate Team Aircraft Design Competition has many design driving requirements. These requirements can be broken down into the following subsections: capacity, performance and biofuels. These subsections will be discussed in detail in the following sections.

1.2.1 Capacity

The RFP for the 2009-2010 AIAA Foundation Undergraduate Team Aircraft Design Competition calls for a replacement for the Boeing-737 Next Generation or Airbus A320. It must be able to carry 175 passengers in a one-class aircraft as well as have room in the cockpit for a crew of 2. The passenger seating must have a pitch of 32” and a width of 17.2”. The aircraft must be able to carry a payload of 37,000 lbs; additionally, there must be 1240 cubic feet of cargo space laid aside for the storage of cargo. This cargo space may be split up between the overhead compartments and a separate cargo hold.

1.2.2 Performance

The RFP also calls for the following performance requirements. To qualify an aircraft must have a cruise Mach number of 0.8 as well as a maximum Mach number of 0.83. The maximum lift to drag ratio must be 25% higher than that of the comparable aircraft to be replaced, in the case of the Boeing 737NG this would be the Boeing 737-800 series. It must have a balanced field length of 8,200 feet or less. The maximum range must be at least 3,500 nautical miles, and must have a maximum cruise altitude of at least 41,000 feet.

1.2.3 Biofuels

The RFP calls for any aircraft that wishes to qualify to be fully capable of utilizing biofuels as the source of fuel for the aircraft. This requirement means that the fuel storage system, fuel pump and piping system and engines must all be capable of handling the selected biofuel. The pumps and pipes must be able to hold and move the fuel from the tanks and to the engines. The fuel storage tanks must be able to handle any changing conditions that are put on the biofuels. Lastly and most importantly, the engines must be capable of using the selected biofuel as the fuel source for the engine.

1.3 Design Drivers

Every requirement in the RFP lays out differing levels of design requirements. Some of these requirements were so major that they required certain assumptions from the start of the design process, these requirements are the RFP's design drivers; they are as follows performance and biofuels. Additionally, there is one other design driver to consider; it is not so much specific to the RFP as it is to all designs, and that design driver is cost.

1.3.1 Performance

Performance has always been a driver in aircraft design; better performance is an expectation these days. The first stages of the design process are always molded by the RFP's performance requirements; this was the case for both the HAWC and SWAT designs. Each of these designs had a different approach to meeting the various performance design criteria; with the HAWC taking the increased wing planform area approach, and the SWAT taking the lower drag, increased wingspan, thinner wings and strut-braced wing design.

1.3.2 Biofuels

Biofuels are a rising factor in the airliner industry these days. Fuel companies have been doing research into various alternative fuels for many years, with biofuels leading the way in recent years. Additionally, as biofuels are considered "green" since they release no additional carbon emissions into the atmosphere; they can be said to have no carbon footprint. The design process of engine selection and several of the systems selection was affected heavily by this requirement.

1.3.3 Cost

For the past few years airline companies have been searching for ways to save money on each individual flights, and several cutbacks have been made. In the design process, decisions were made early on to cut back on materials cost in manufacture and fuel cost per flight. Meeting the performance requirement of increasing the maximum lift to drag ratio will assist in the fuel consumption cost per flight; therefore the designs were planned to not only meet, but exceed the maximum lift to drag ratio requirement to further reduce fuel cost on a flight by flight basis.

1.4 Biofuels

The RFP demands that SWAT can use biofuels in its engine and propulsion system. Biofuels are not a new concept. The Ford Model T, produced between 1903 and 1926 was specifically designed to run on ethanol but when crude oil began being cheaply extracted from the ground, demand for the cheaper petroleum-based fuels negated the need for the biologically produced fuel alternative, biofuel. In recent years, renewed interest in biofuels in the United States has sparked due to many factors, among them (1) increases in world fuel prices and (2) political instability in petroleum producing nations in the Middle East.

Currently, biofuels make 3% of the US transport fuel market, the two primary types being ethanol and biodiesel.[19] Added to these two primary sources are two promising fuel alternatives: algae-produced oil and bio-butanol.[20]

The Request for Proposal calls for an alternative fuels system that specifically uses biofuels. The present section examines promising fuels that were considered in designing the system required by the RFP. These are (1) ethanol, (2) biodiesel from food crop sources, and (3) algae fuel.

After a careful analysis of these candidate fuels, algae fuel was found to be the top contender for having the most advantages over current Jet-A fuel, as well as having drawbacks that are only limited by the economic environment; the reasoning behind this decision will now be explained in detail.

1.4.1 Ethanol

Ethanol is a fuel produced by common crops such as sugar cane or corn grasses that go through processes such as fermentation, distillation, and dehydration. Combustion engines can run on gasoline with as much as 10 percent ethanol in them without having to make any mechanical modifications, but as the concentration of ethanol increases special engine modifications are also needed. Automobiles already exist that that have these modifications and similarly aircraft can be modified to operate on ethanol fuel.

The source of this ethanol is referred as biomass, which is "any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials."[21] The principle source of biomass in the U.S. ethanol industry is corn because it is readily fermentable and can produce high yields of ethanol per crop. An obvious economic advantage of using ethanol instead of petroleum-based fuel is that unlike crude oil, which is the source of current fuel used in aircraft, no one country dominates the market for ethanol. Therefore, regardless of national petroleum reserves, the US can produce ethanol domestically or purchase it on the open market from a wider range of nations. Additionally, whereas petroleum releases carbon that had been previously trapped underground, the carbon in biofuel emissions has simply been captured from the atmosphere by crops during photosynthesis. The effect of completely switching to ethanol is up to a 90 percent reduction in greenhouse-gas emissions due to recycling carbon as opposed to releasing it into the atmosphere. A third advantage of ethanol is the price. In Brazil, with 30 percent of automobiles running on ethanol, it is less than half the price of crude oil at only $25 per barrel.[22] These three characteristics of ethanol make it an attractive and affordable alternative to petroleum-based fuels because it offers economic and environmental advantages over petroleum based fuels. In April 2005, the U.S. Department of Energy and the U.S. Department of Agriculture published the joint study titled, “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The technical Feasibility of a Billion-Ton Annual Supply.” The purpose of the study was to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass in order to replace only 30 percent of current U.S. petroleum consumption by the year 2030.[23] The study determined there is enough biomass, looking at just forestland and agricultural land, to produce over 1.3 billion dry tons of biomass per year. The nearly one billion dry tons of biomass derived from agricultural sources would require only modest changes in land use, and would not impact U.S. ability to meet food, feed and export demands. As a result, the U.S. Department of Energy and the U.S. Department of Agriculture are both strongly committed to expanding the role of biomass as an energy source.

However, the same study concluded that a future ethanol fuel industry would indeed need to have a large amount of funding, even larger than the other two candidate fuels. Additionally, in order to meet the RFP requirement of an alternative system by the year 2020, it is less likely to have an industry capable of supporting the airline industry.

1.4.2 Biodiesel (from food crop sources)

Although ethanol offers advantages to petroleum-based fuels, it is only one of several biofuels under development. Much like ethanol produced from biomass sources, biologically produced diesel fuel, or biodiesel, has been in existence for over 100 years. In 1853, scientists E. Duffy and J. Patrick completed the first process of exchanging the organic group R" of an ester with the organic group R' of an alcohol of a vegetable oil producing manmade diesel fuel. Current biodiesel use is typically limited to a 5% mixture with petroleum-based diesel but produces no ill effects to those engines using the blended fuel. As oil prices increase, and with increased emphasis on reducing environmental impacts of petroleum use, biodiesel use has grown.[24] Therefore the main advantage that biodiesel has over the other two candidate fuels is that it has the most developed infrastructure and has already been proven to work in the US economy for a number of years, and has the biggest presence in legislation.[25] In 2005, Minnesota became the first and only state requiring that all diesel fuel sold be mixed with biodiesel.[25]

There are several sources of biodiesel. Virgin oil feedstock such as rapeseed, and soybean oils are most commonly used, though other crops such as mustard, palm oil or hemp can be grown to produce biodiesel. A second source of biodiesel is waste vegetable oil. Advocates of biodiesel suggest waste vegetable oils offer the best source of oil to produce biodiesel since restaurants produce over 300 million gallons annually. Although waste oil offers a profitable method for obtaining biodiesel, other products made from waste oil, such as soap, offer even higher profit margins and therefore compete for biodiesel feedstock. A third source of biodiesel is animal fats. Since animal fats are typically discarded and not used for other applications, their use as a source of biodiesel is only limited by the comparatively small amount available.[23]

Regardless of the source of biodiesel, the process used to obtain the diesel is the same. The process is used to convert the base oil to the desired ester. Any free fatty acids in the base oil are either converted into soap and removed from the process or they are esterified (producing more biodiesel) using an acid catalyst. After refining, biodiesel has combustion properties very similar to those of petroleum diesel.

The main disadvantage is that biodiesel would typically compete with the food supply and therefore it is limited in the amount of supply that can be produced. It is also limited by a high viscosity that can mean current aircraft engines need to be redesigned around this principle. A third major disadvantage is the carbon footprint, since biodiesel would typically not be used as a fuel wholly, meaning that Jet-A fuel would still be used as the main component.

1.4.3 Algae Fuel

Just like terrestrial plants, algae can be grown to produce oil. The National Renewable Energy Laboratory (NREL) has extensive experience cultivating and manipulating microalgae to produce lipids or oils. Microalgae naturally store oil when denied nutrients used for growth and energy. An advantage of producing oil with algae is that unlike terrestrial-based plants, algae do not require precipitation or good soil, all they require is carbon dioxide, sunlight and saline water in which to grow. It is also possible to refine the lipids to diesel and gasoline for use in other military or civilian chemical composition more like a petroleum product than a biomass-derived product. While it is technically possible to carry out the second step, lipid refining, with plant-based lipids, e.g. soybean oil or rapeseed oil, the quantity of oil feedstock required to meet Department of Defense needs exceeds the available supply of these plant-based oil vehicles. These refined finished products would contain near-zero oxygen, and would have a chemical composition more like a petroleum product than a biomass-derived product.

Algae oil offers a solution since such fuel can produce oil under conditions that are unsuitable for traditional agriculture. Although areas like the desert Southwest or seashore are unsuitable for typical crop growth, by making use of man-made cultivation ponds, algae can flourish in these otherwise sparse environments. It was originally believed that inexpensive shallow ponds provided the most cost-effective way to grow algae. Table 1.1 shows a comparison of oil production from traditional biological sources. With the research NREL is proposing, it may be possible to achieve lipid productivities per acre that far exceed terrestrial plants. Algae oil production of more than 50 times that per acre of traditional oilseed crops may be achievable, yielding as much as 15,000 gallons of oil per year. In addition to closed ponds, the low cost of plastic containers offers the possibility of growing algae in closed systems such as transparent tubes with even greater yield rates possible.

Table 1.1 - Biofuel Yearly Yield Per Acre

Production Feedstock	Gallons of Oil per Acre/Yr
Corn	18
Soybeans	48
Safflower	83
Sunflower	102
Rapeseed	127
Oil Palm	635
Micro Algae	5,000 – 15,000

To produce high yields of oil, algae require a huge supply of carbon dioxide. One potential solution is placing algae pools next to coal burning power plants. According to Isaac Berzin, founder of Greenfuel, “just one 1,000 megawatt power plant using this system could produce more than 40 million gallons of biodiesel and 50 million gallons of ethanol a year.[23] That would require a 2,000-acre “farm” of algae-filled tubes near the power plant. There are nearly 1,000 power plants nationwide with enough space nearby for a few hundred to a few thousand acres to grow algae and make a good profit.” In addition to thriving under conditions unsuitable for other crops, and thereby preserving arable land for food production, the properties of algae produced oil are superior to oil produced by terrestrial means. Another major advantage is its carbon neutral principle. The alga takes in carbon dioxide during growth and then released back during combustion.

The major disadvantage is that algae fuel is relatively new and unproven in the US economy. Also, there is no infrastructure yet to support an airline industry, something that would need to be built to meet the 2020 target of the RFP.

Table 1.2 - Properties of Algae Fuel and Jathropa Plant Fuel (a biodiesel)

	Jet A-1	**Algae Fuel**	**Jatropha Plant Fuel**
Flash point	38 °C (100.4 °F)	65-115 °C (149-239 °F)	46 °C (114.8 °F)
Auto ignition temperature	210 °C (410 °F)	210 °C (410 °F)	340 °C (644 °F)
Freezing point	−40 °C (−40 °F)	−40 °C (−40 °F)	-57 C
Density at 15 °C (59 °F)	0.8075 kg/L	0.775-0.840 kg/L	0.749 kg/L
Specific (gravimetric) energy density	43.15 MJ/kg	43.15 MJ/kg	39.628 MJ/kg
Volumetric energy density	34.69 MJ/L	33 MJ/L	33 MJ/L

1.4.4 Energy Density

The first criterion that must be satisfied is energy density. The aircraft's turbine engine transforms chemical energy stored in the fuel into thrust that pushes the aircraft forward thus resulting in flight. When burning hydrocarbon fuels such as Jet A, the fuel energy is released during combustion, a rapid reaction with oxygen at a high temperature. Combustion is described by the following equation:

$$CxHy + (x + y/4)\,O2 \rightarrow x\,CO2 + y/2\,H2O + heat$$

The ideal aircraft fuel would minimize both mass and volume for a given energy content. Aircraft are rated to takeoff at a specific maximum takeoff weight (MTOW) that includes the weight of the aircraft, passengers, cargo, weapons and fuel. If an aircraft reaches MTOW before its fuel tanks are full, a fuel with a higher energy per pound, gravimetric energy content, will allow the aircraft greater range. Accordingly, a fuel with low gravimetric energy content would force a shorter range or require additional aerial refueling in order to accomplish a similar mission.

Energy per gallon, volumetric energy content, is just as important. Once an aircraft reaches full fuel capacity, its unrefueled range is set. A lower volumetric energy content fuel reduces combat range and in turn reduces combat capability. The only solution is to either accept limited flight range, or to spend increased time flying to and from a tanker in order to accomplish the same mission as an aircraft fueled with a high volumetric energy content fuel.

Although the primary function of jet fuel is as a source of energy, fuel is also used to cool avionics and serves as a lubricant in engine systems and pumps. Therefore, in order to prevent fleet wide engine modifications, a suitable alternative fuel must not only meet energy density requirements, but must also meet this secondary performance specification in order to adequately replace Jet A fuel.

Algae fuel offers additional storage challenges. First, biodiesel "ages," that is to say viscosity increases with time. Already a highly viscous fuel, biodiesel becomes unusable in as little as six months. According to the National Biodiesel Board biodiesel must be used within six months of manufacture to guarantee fuel quality. The second challenge already discussed is microbial growth. Biodiesel must be continuously monitored to ensure fuel purity.

1.5 Struts

Struts were utilized on the SWAT design to support a large portion of the load on the wing, specifically reducing the maximum bending moment on the wing. The SWAT design effectively utilized the strut-braced wing concept to allow for an increased aspect ratio, thinner wings, lower sweep and increased span. This will allow the SWAT to maintain laminar flow over the main wing while at the cruise Mach number of 0.8; additionally, it also will gain the benefits of reduced drag and weight which will allow for the SWAT design to have lower fuel consumption for its flights.

2 Design Evolution

2.1 Design Concepts

After determining the design drivers from the RFP, two primary concepts were investigated. These two concepts came from two alternative approaches to meeting the maximum lift to drag ratio increase required by the RFP. The HAWC design, originally the HABW, started with the idea of utilizing a larger wing planform area; whereas the SWAT design focused on an increased wingspan and strut-braced wing support system.

2.1.1 HAWC Design

The HAWC concept is a high-area wing configuration transport jet designed to run on alternative fuels. The design is modeled closely to the Boeing 737-800 with a few modifications intended to improve aerodynamic characteristics and allow for an alternative fuel system to be implemented.

Originally, this design was a high-area blended wing concept modified from a Boeing 737-800. The original sketches can be seen in Figures 2.1-2.3:

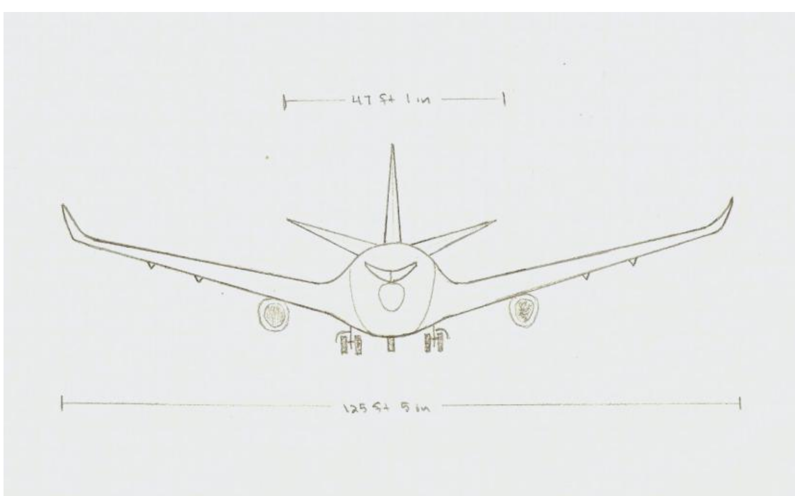


Figure 2.1 – Front view of original high-area blended wing design.

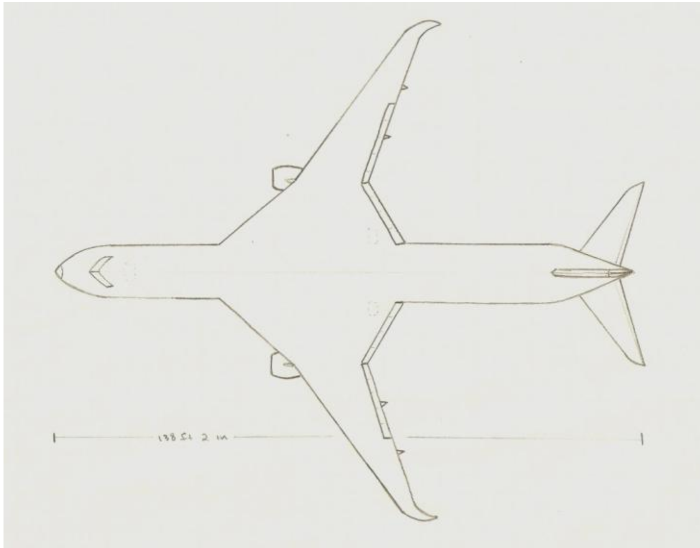


Figure 2.2 – Top view of original high-area blended wing design.

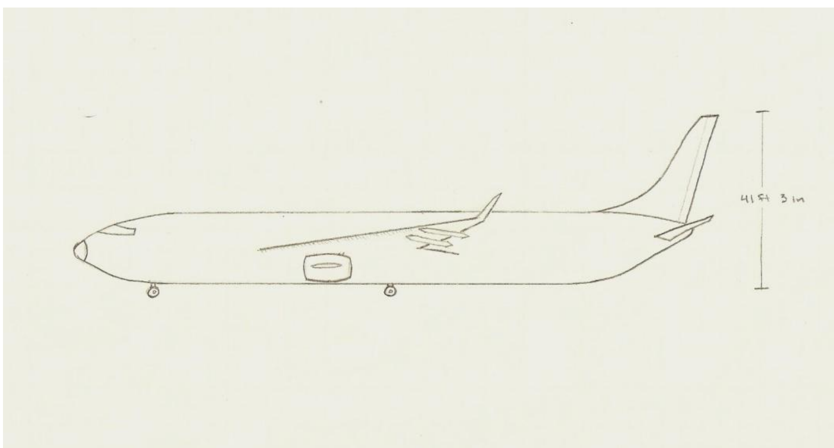


Figure 2.3 – Side view of original high-area blended wing design.

The original intention of choosing the high-area blended wing (HABW) body design was to maximize overall efficiency by integrating the wings and the body to create a single lifting surface. The greater surface area of the combined wing and body was thought to potentially produce greater lift compared to the traditional 737 design. This design would also increase the internal volume of the aircraft leaving more room for passengers, cargo, and most importantly fuel. Knowing that this aircraft will eventually run on alternative fuels, the larger internal volume will be a key feature of this final design.[4]

Ultimately, after a great amount of research, the design was determined not to fit the requirements of this project. The HAWB is not a traditional blended wing body (BWB) or “flying wing” design, but it would exhibit some of the same characteristics. While the idea for a “flying wing” aircraft is not new, no commercial transport of this type has ever been created. The issues of high-speed aerodynamics, propulsion integration, and cabin pressurization all contribute to the complexity of this design concept. On top of that, most of the existing designs are large enough to carry up to 800 passengers over a range of 7000 miles. It seems that the larger the aircraft the more efficient the BWB (and in theory the HABW) becomes. Unfortunately, such a large aircraft requires a large wing span which may not integrate well with the airports of 2020. Most importantly, the RFP only calls for a 175 passenger transport to travel a maximum range of 3500 nm. These factors led to the dropping of the HABW design in exchange for a simpler high-area wing configuration (aka HAWC).

The high-area wing configuration or (HAWC) was chosen because it has the advantages of a HABW (to an extent) without the added complexity and overly large size. Figures 2.4-2.6 show the Rhino drawings of the HAWC design concept:

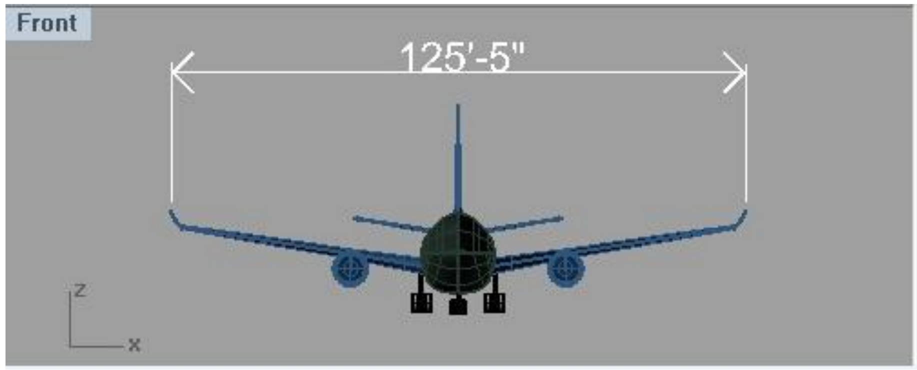


Figure 2.4 - Front view of HAWC design.

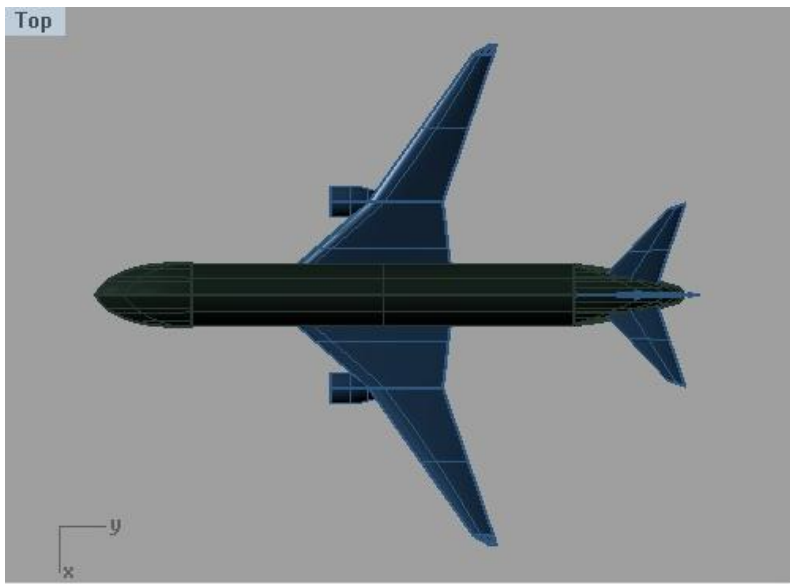


Figure 2.5 - Top view of HAWC design.

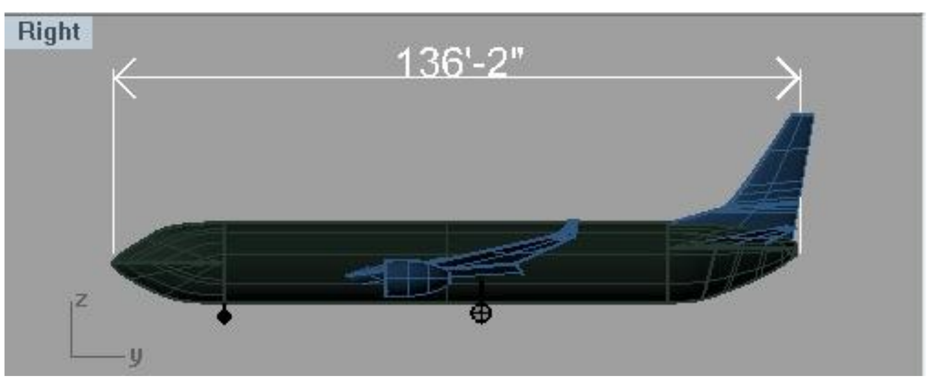


Figure 2.6 - Side view of HAWC design.

Much like the HABW, the HAWC design was modeled after the traditional Boeing 737-800. The main difference is that the wing was modified to have a 10% increase in total area. This larger wing area provides the desired increase in internal volume, for an increased amount of fuel, as well as allowing for a lower wing loading than a comparable transport aircraft.

The technical definition for wing loading is the loaded weight of an aircraft divided by the area of the wing, W/S. The larger wing area and comparable weight, to the 737-800, of the HAWC lead to a lower wing loading. This factor contributes to more lift at any given speed than a conventional transport aircraft. Therefore, an aircraft with a lower wing loading will be able to take-off and land at lower speeds, or with a greater load. The lift force, L, over the wing area, S, is given by Equation 1:

$$\frac{L}{S} = \frac{1}{2} U^2 \rho C_L \qquad (1)$$

Where U is the speed of the aircraft, ρ is the density of the air, and C_L is the lift coefficient. At take-off or in steady level flight (no climbing or diving) the lift and the weight are equal which allows for an equation for take-off aircraft speed with respect to wing loading:

$$U = \sqrt{\frac{2g\frac{W}{S}}{\rho C_L}} \qquad (2)$$

Using this Equation 2 it can be seen that a 10% increase in wing area leads to an approximately 5% decrease in take-off speed.[5]

Wing loading is also a useful measure of the general maneuverability of an aircraft. A larger wing area means that there is increased airflow over the wing. Aircraft with low wing loadings tend to have superior sustained turn performance because they can generate more lift for a given quantity of engine thrust. An aircraft with a high wing loading may have a better instantaneous turn response, but may not be able to hold a tight turn for very long. The smaller the wing loading the tighter and longer the turn.[5]

One of the negative aspects of this design is the increased gust response caused by the larger wing area. A gust produces an upward pressure on an aircraft, effectively decreasing its wing loading and subjecting it to increased noise and turbulence. An aircraft with excess turbulence will not please passengers and make this design a tough sell to an airliner.

In order to make the increased area of the wing work the taper ratio had to be very small. This design aspect commonly leads to a phenomenon called tip stall. This is the stall of the outer portion of the wing which may have an increased angle-of-attack compared to the rest of the wing. As can be seen in Figure 2.7, tip stall can effectively move the centers of pressure for each

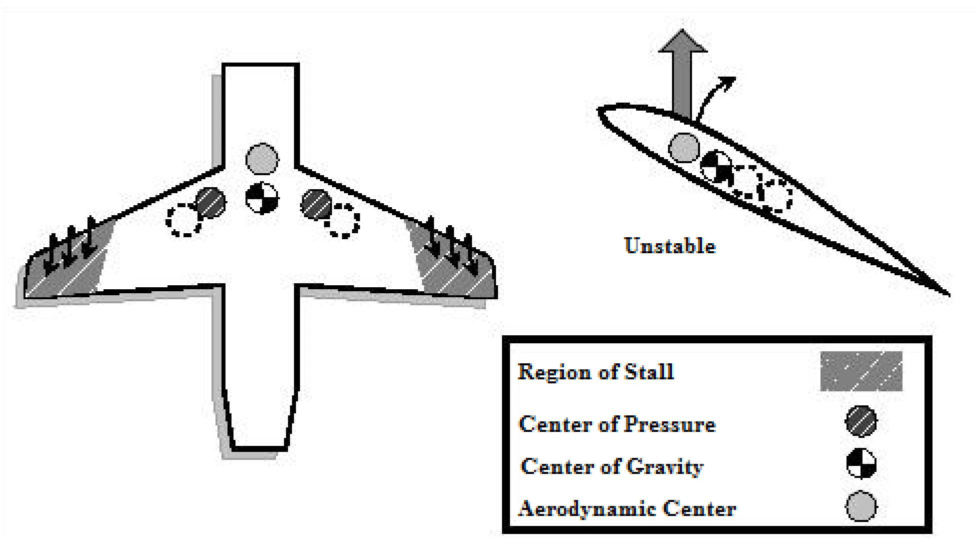


Figure 2.7 - Representation of Tip Stall [31]

wing forward and in. This, in turn, shifts the aerodynamic center forward. If the aerodynamic center moves in front of the center of gravity the aircraft could experience an uncontrollable pitching moment. The control surfaces would be unable to counteract the moment because of the stall rendering them useless. An unstable aircraft is not marketable or realistic.[4]

For the purposes of this project and the RFP, the negatives of this design slightly outweighed the positives. Additionally, the SWAT design was showing agreeable results which made the final decision straight forward. A high-area wing configuration would be abandoned for a strut-braced wing (and T-tail) design.

2.1.2 SWAT Design

The idea behind the SWAT design was to improve the aerodynamics and lighten the aircraft to gain advantages in L/D and takeoff distance. Also the fuel efficiency was to be improved by reducing drag on the aircraft and improving the aerodynamics of the aircraft. Also a high wing and T-tail were to be used to achieve many of these goals. Struts were also used to allow for lighter longer wings.

The aerodynamics improvement came from wing sweep and the struts which allow it to have thinner wings. The thin wings came from the fact that the wing no longer has to support its entire weight since part of that weight is supported by the strut braces. Thin wings will allow for a reduction in subsonic profile drag. This decrease comes from the fact that the skin friction will be smaller since there will be less skin to interact with the flow and there is a potential decrease in form drag from the decrease in thickness which prevents the wing from being so thick that the flow separates. One problem with the thin wings is that the weight of the wing will be heavier since bending and torsional stiffness is reduced by decreasing thickness. Another downside to thin wings is the decrease in fuel storage within the wings which forces more of the aircrafts fuel into the fuselage which can account for a larger shift in the center of gravity of the aircraft. This shift can be minimized by storing the fuel around the center of gravity. The presence of the struts will allow for the wing improvements but will create additional drag, thus reducing some of the positive effects of thin wings, and some potential structures risk requiring a precisely sized and shaped strut. Another source of improved aerodynamics is the T-tail which allows for a smaller and more efficient horizontal tail due to the fact that it is removed from the wake of the wings and engine. The downside of a T-tail is that it has increased weight to support the lifted horizontal tail. Also it can create an increased risk of deep stall at high angles of attack. This design should allow for the desired increase in overall L/D and a decrease in the overall drag.

The fuel efficiency was achieved by an overall decrease in drag across the aircraft as well as the engine and fuel selection that was mentioned earlier in the report. This as well as the eCore considerations for the future, which allows for a 16% lower fuel burn expectation in our engines by the year 2020.[17] Since the RFP specifies a production date of 2020 and beyond; this is a valid assumption to make. This increase combined with the aerodynamic improvements in lift and drag should allow for the RFP desired fuel efficiency improvement. Emissions will also be reduced by the selection made for the engine as well as the fact that the biofuel selected will allow for a carbon neutral carbon footprint. Even though the one consideration that is most important with this is forcing fuel efficiency in the engine because although this design will be carbon neutral from the fuel selection the destination of the emitted emissions is directly in the atmosphere. This is undesirable since this is exactly where those emissions do the most damage. Therefore engine selection is an important part of the design as shown earlier.

The final main design constraint was the lightening of the aircraft to improve the TOGW and cruise weight thus allowing for more fuel efficient and better lift to drag relationship. This was accomplished through the use of composites for much of the structural components. This will allow for the weight reduction that will aid the other design constraints from the RFP.

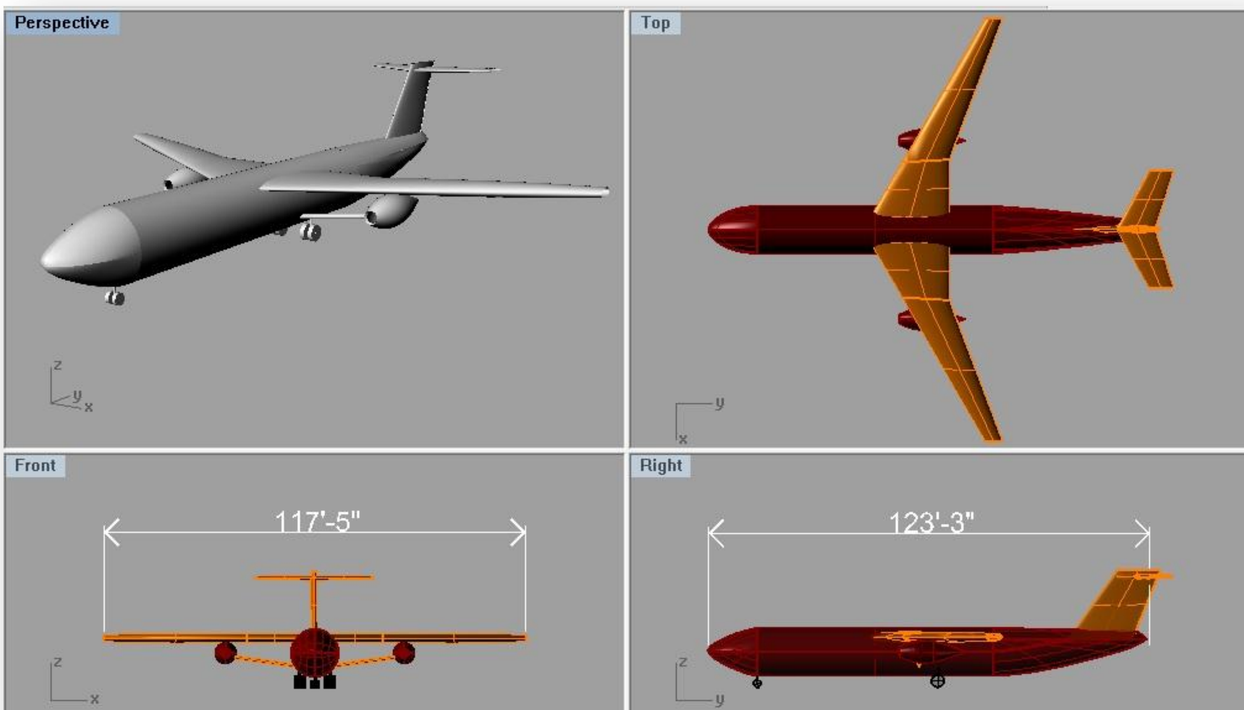


Figure 2.8 – Rhino Drawing of SWAT Design – Early Stages

Figure 2.8 shows the three view and perspective view of the SWAT aircraft in its most recent design. Initially it was a low wing design. This was changed due to the fact that it allowed for better implementation of the struts. The high wings will also allow for shorter and thus lighter landing gear. The high wing also allows for large wing flaps which allow for high lift coefficient.

There are also disadvantages for a high wing configuration. One disadvantage is a higher fuselage weight for the landing gear box and the high wing box.[1]

The T-tail has pros and cons as well when approached from the perspective of the given RFP. It has an increased weight for supporting the horizontal tail as previously stated. It does however allow for more efficient horizontal tail since it is outside of the wake of the engines and wings. Also along with that the smaller horizontal tail the vertical tail can have a smaller area due to the endplate effect. These size reductions create a reduction in stress over the tail allowing for an increase in the life span of the tail. Another pro is that it has the style bonus, which when one considers the fact that the RFP calls for creating a replacement for a commercial aircraft; one must consider the opinion of the customer and their customers. When compared to the simple bonus of the conventional tail in reduced weight and the downside of reduced efficiency and life span the T-tail was a clear choice. [1]

The design has undergone a primary change since the original report and has a new wing span of 140 feet as well as a new sweep angle. The sweep angle has been reduced to 12° on the leading edge and 10° on the trailing edge. This allows the design to have an even higher maximum lift to drag ratio as well as decreasing the wing weight due to reducing the wing sweep and allowing for a thicker wing. The increase in span has an issue with not being within the normal hangar wingspan size; this was the reason for the choice in the original wing span shown in Figure 2.8.

The design also evolved to allow a positive dihedral on the horizontal stabilizer as this allows for additional control assistance. This assists the SWAT design in meeting its stability requirements set out by the FAA FAR and MIL-STD. For most of the requirements the MIL-STD was used for the SWAT design since it has a more simplistic and understandable way of describing the requirements. This will be discussed later in section 6.

2.2 Sizing

The initial dimensions of the SWAT and HAWC designs were input into a Visual Basic program made by David Pfister of Slipstream Aerospace, which utilized the following method from Raymers book: [1]

Fuel burned for each mission segment:

$$W_{fi} = \left(1 - \frac{W_i}{W_{i-1}}\right) W_{i-1} \tag{3}$$

Fuel burned additional allowance for each segment, increased to 10% to allow for additional missed approach range:

$$W_f = 1.1\left(\sum_{1}^{x} W_{fi}\right) \tag{4}$$

Takeoff segment:

$$\frac{W_i}{W_{i-1}} = 0.97 \; to \; 0.99 \tag{5}$$

Climb and Accelerate segment:

$$\frac{W_i}{W_{i-1}} = 1.0065 - 0.0325M \tag{6}$$

Cruise segment:

$$\frac{W_i}{W_{i-1}} = \exp\left(-\frac{RC}{V\left(\frac{L}{D}\right)}\right) \tag{7}$$

Descent segment:

$$\frac{W_i}{W_{i-1}} = 0.990\ to\ 0.995 \tag{8}$$

Landing segment:

$$\frac{W_i}{W_{i-1}} = 0.992\ to\ 0.997 \tag{9}$$

Each segment adds up to provide the total fuel burned for the total aircraft mission. To calculate the empty weight the following formula and constants were used.

$$\frac{W_e}{W_0} = \left(a + bW_0^{C1}A^{C2}\left(\frac{T}{W_0}\right)^{C3}\left(\frac{W_0}{S}\right)^{C4}M_{max}^{C5}\right)K_{vs} \tag{10}$$

Where for a jet transport:

$$a = 0.32 \quad b = 0.66 \quad C1 = -0.13 \quad C2 = 0.30 \quad C3 = 0.06 \quad C4 = -0.05 \quad C5 = 0.05$$

For a fixed sweep wing $K_{vs} = 1.00$ for both the HAWC and SWAT, the wing sweep was fixed.

After that the aircraft's wing and tail sizes were recalculated and the sketch redrawn; then the method was continued until the changes in size were minor. This method provides an accurate accounting of what the weight and design sizing should be based on a logical iteration until the size converges to a single value.

Ultimately the iterative method converged to a TOGW, fuel weight and wing planform area of 191400 lbs, 56652 lbs, and 1539.25 ft^2. While this iterative method is good for early designs; it is not precise enough to do some of the more accurate portions of the sizing method. For these accurate methods the following formulas were utilized from chapter 6 and 19 of Raymers. [1]

$$\frac{L}{D} = \frac{1}{\frac{qC_{D0}}{W/S} + \frac{W}{S}\frac{1}{q\pi Ae}} \tag{11}$$ [1]

Where L/D is the cruise L/D in this case, this time L/D was not considered constant and it varied as the input of W/S varied.

This method was fully implemented in the final HAWC and early SWAT concept designs. A few formulas used to calculate values needed for the aircraft was as follows:

$$S_{wet} \cong 3.4\left(\frac{A_{top} + A_{side}}{2}\right) \tag{12}$$

To calculate the wetted area of the wing the previous formula was used where A_{top} is the reference wing area and A_{side} is the fuselage area from a side view.

$$C_{D0} = C_{fe}\frac{S_{wet}}{S_{ref}} \tag{13}$$

Parasite drag is calculated with the previous formula using a $C_{fe} \cong 0.0030$ for civilian transport aircraft.

$$K = \frac{1}{\pi Ae} \tag{14}$$

The Oswald efficiency factor for a civilian transport is approximately e = 0.8; and this allowed the calculation of K.

$$\left(\frac{L}{D}\right)_{max} = \frac{1}{2\sqrt{C_{DO}K}} \tag{15}$$

Once K was known the $\left(\frac{L}{D}\right)_{max}$ could be calculated using parasite drag. These formulas were all added to the Visual Basic program, Aircraft Design, made by Slipstream Aerospace to allow for increased accuracy.

The results from the final run after iterating, comparing with requirements and then inputting the final data in Slipstream Aerospace's program are shown in Table 2.1. Additionally, a new TOGW, fuel weight and wing planform area was found for the SWAT design; 174590 lbs, 39777 lbs, and 1454.91 ft^2 respectively.

Table 2.1 – C_{D0} and L/D_{max} comparision

	C_{D0}	L/D_{max}
HAWC	0.01063	18.24
SWAT	0.01624	22.83

2.3 Decision Matrix

Each design was given a rating that corresponds to a category for the design matrix, low scores were used to illustrate the best in that category. Meeting the RFP requirements means that the aircraft has to meet all the requirements of the RFP and then is compared to the other competitors to see which meets it best, as the Boeing 737-800 series cannot hope to achieve the RFP requirements as that is the comparable aircraft which must be upgraded it was given the worst score in that category from the start. Service life is the expected lifetime of the aircraft based on known factors that affect aircraft wear, such as turbulent flow passing over the wings. Maintenance is how easy the aircraft will be to maintain, ease of access to the engines, etc. Marketability is based on how the consumer and passenger will react to the aircraft design, basically is it likely to sell or not. Stability was based on the early stability calculations from the aircraft. Complexity means is the design difficult to manufacture and is the design less simple than the competitors. Originality is based off the RFP request for an original design, something that has not been seen before. Cost is based off of the early cost analysis done based off of size, material needs and engine requirements. Table 2.2 shows the decision matrix for the HAWC and SWAT designs versus the current market competitor, the Boeing 737-800 series, the lowest rating on the 1-3 scale is the best rating.

Table 2.2 – Qualitative Decision Matrix

	Importance	Weight	HAWC	SWAT	737-800
Meets RFP	1	10	2	1	3
Service Life	2	8	3	1	2
Maintenance	2	8	1	2	1
Marketability	3	6	3	1	2
Stability	4	4	2	1	1
Complexity	5	3	2	3	1
Originality	5	3	2	1	3
Cost	5	3	2	3	1
Total	-	-	96	65	85

As is shown in Table 2.2, the SWAT design had the lowest score and therefore the best score by far. The main reason for this was that it not only met but exceeded the primary RFP requirements even in the early stages of development. Additionally it had greater capability to exceed the stability and balanced field length requirements; as well as provide an original, yet marketable product.

3 Weight

3.1 Weight Statement

The weights for this aircraft were found by breaking down the airplane into its various components, and then estimating a weight for each component. Various equations were used to estimate the weight of each component.[1] The values for each component are listed in Table 3.1.

Table 3.1 – Weight of Components for SWAT

Component	Weight (lbs)
Wing	7,042
Horizontal Tail	851
Vertical Tail	2,634
Fuselage	19,771
Main landing gear	2,636
Nose landing gear	1,488
Nacelle group	160
Engine Controls	130
Starter (pneumatic)	175
Fuel system	1,297
Flight Controls	895
APU installed	858
Instruments	191
Hydraulics	272
Electrical	687
Avionics	1,689
Furnishings	3,228
Air Conditioning	3,666
Anti-ice	339
Handling gear	34
Engine	10,432
Empty Weight	**58,474**
Fuel	39,777
Operating Weight	**98,251**
Cargo	37,000
Take Off Weight	**135,251**

Table 3.2 compares the various weights of SWAT under difference conditions against the Boeing 737-800, as well as the Airbus A320-200 configured with the CFM56 engine, under the same conditions. All three of these airplanes carry around 175 passengers and have similar mission profiles, which allow them to be compared to each other. The SWAT comes in with a max takeoff weight of 38,553 lbs under the Boeing 737-800, and 36,749 lbs under the Airbus A320-200.

Table 3.2 – Weight comparison of airplanes under different conditions

Weight (lbs)	**SWAT**	**Boeing 737-800**	**Airbus A320-200**
Empty Weight	58,474	91,108	94,000
Max Fuel Weight	39,777	46,200	41,480
Max Operating Weight	98,251	137,308	135,480
Max Cargo Weight	37,000	36,496	36,520
Max Takeoff Weight	135,251	173,804	172,000

3.2 Center of Gravity Travel

The center of gravity was found by taking each of the moments from each of the components of the aircraft. The moments were summed and then the sum was divided by the total current aircraft weight. This was done for each of the major situations a commercial airliner will encounter, full, no fuel, no payload and empty. The detailed results for each of these are shown in Table 3.3.

Table 3.3 – Center of Gravity Travel Locations

Condition	Center of Gravity	Static Margin
Full	58.7 ft	10%
No Fuel	59.0 ft	7.6%
No Payload	57.9 ft	16.4%
Empty	57.8 ft	17.2%

4 Propulsion

4.1 Engine Selection

Since the CFM56-7B Series is currently used on numerous cargo/transport aircraft, as well as being known as very reliable, its engines were considered for the performance aspect of SWAT.

The three engines taken into account for this aircraft were the CFM56-7B24, CFM56-7B26, and CFM56-7B27. The various performance specifications of these three engines are shown in Table 4.1.

Table 4.1 - Performance Specifications of Engines

	CFM56-7B24	CFM56-7B26	CFM56-7B27
Airflow (lb/sec)	751	779	782
Bypass Ratio	5.3	5.1	5.1
Dry weight (lbs)	5216	5216	5216
Fan diameter (in)	61	61	61
Length (in)	98.7	98.7	98.7
Pressure Ratio	32.8	32.8	32.8
SFC (dry) (lb/lbf hr)	0.37	0.38	0.38
Thrust (lbs)	24,200	26,300	27,300
Dry Weight (lbs)	5,216	5,216	5,216

Many of the performance characteristics and specifications were similar for the three engines, with the main difference being the maximum thrust produced. The CFM56-7B26 was decided as the engine that would be used since the extra thrust that the other two engines provide is not a necessity. Also, the dry weight of all three engines is the same, making the engine weight a non-issue. The maximum thrust for these three engines is shown in Figure 4.1, with the CFM56-7B26 engine being shown in Figure 4.2.

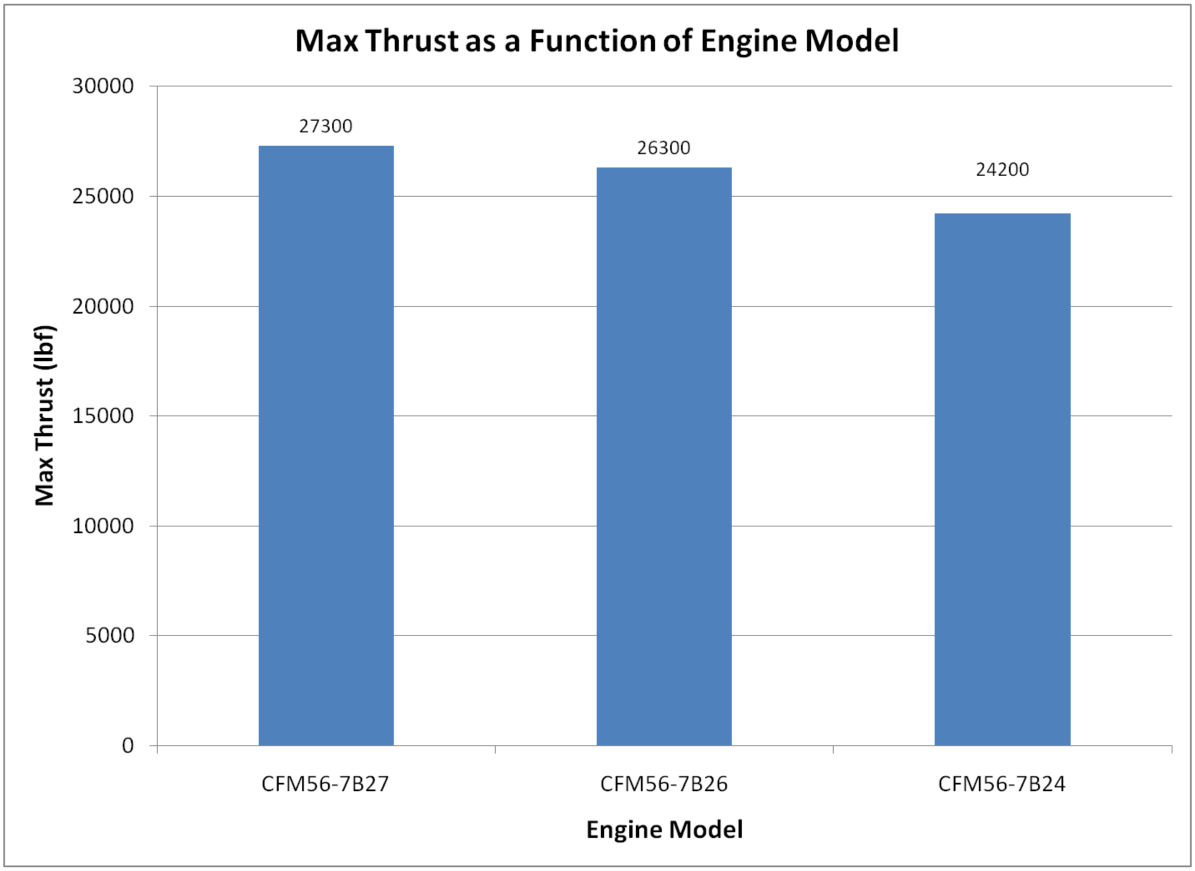


Figure 4.1 - Max Thrust of Proposed Engines

Figure 4.2 - The CFM56-7B24 Engine [2]

4.2 Auxiliary Power Unit

To start the turbine engines on SWAT an Auxiliary Power Unit, also known as an APU, will be utilized. The SWAT will use the Delphi Solid Oxide Fuel Cell APU because of its increased efficiency over current market standards. It boasts greater than 50 percent efficiency and uses Carbon Monoxide as a fuel to prevent cleanup in the reformatting process. It also has 440kW of electrical power and can operate up to an altitude of 43000 feet; in accordance with FAA regulations an onboard inert gas generation system will be used on the SWAT.

5 Aerodynamics

According to the requirements, the airplane is to be able to land at a speed of 140 knots, cruise at a speed of Mach 0.8, at an altitude of 35,000 feet with low drag. To be able to achieve these goals a good wing design had to be used, this design has to allow the airplane to takeoff at a safe speed and a takeoff distance of 8200 feet. The struts on the wing allowed the design of a wing with a high wingspan and a thin airfoil. Also the thin airfoil allowed the use of a low sweep angle. Thin airfoils reduce wave drag caused by shockwaves in the transonic speed range. Having a high wingspan meant that the chord length can be small, and this is desirable to delay the transition point over the chord length. Having laminar flow on most part of the wing instead of turbulent flow reduces skin friction drag. Honda experiments have shown that the transition point can be delayed up to 80% of the wing chord. Airbus has also had some tests showing the effect of the wing sweep and the Reynolds number on laminar flow. Figure 5.1 shows some the experiments they conducted and also it shows the range our airplane would lie in.

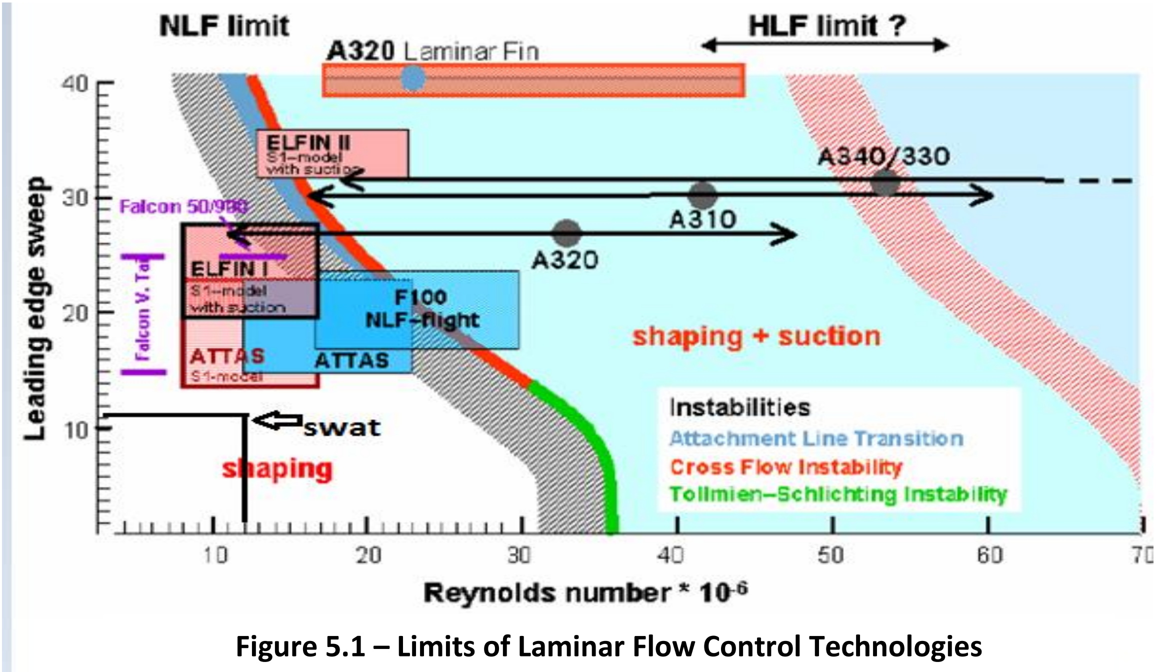


Figure 5.1 – Limits of Laminar Flow Control Technologies

AIAA 2008-3738

5.1 Airfoil Selection

The wing area was chosen during the initial design and this was done based on the wing loading and thrust to weight ratio. The wing sweep and airfoil thickness were used to find the airfoil requirements by utilizing the Korn equation.

$$M_{DD} = \left(\frac{k_A}{cos(\Lambda)}\right) - \frac{t/c}{cos(\Lambda)^2} - \frac{C_L}{10\,cos(\Lambda)^3}$$

The divergence Mach number was found to be 0.803; the technology factor used was that of a supercritical airfoil 0.95 is. From this equation the airfoil parameters can be determined. Table 5.1 shows some of the wing planform parameters.

Table 5.1 - Wing planform parameters

Root chord (ft)	17.6
Tip chord (ft)	5
Span (ft)	140
Area (ft^2)	1454
Leading edge sweep (deg)	12
Aspect ratio	13.2
Mean aerodynamic chord	12.5
Taper ratio	0.54
Thickness to cord ratio	0.1

The airfoil for the main wing was selected using the Korn equation which relates the airfoil lift coefficient, thickness to chord ratio and sweep angle. The drag divergence Mach number was fixed to the RFP cruise Mach number of 0.8 and then was iterated for the three most common thickness to chord ratios of airfoils from a 0° to 30° sweep angle. Figure 5.2 shows the resulting data. For the SWAT design a sweep angle of 12° was selected and for wing fuel storage considerations a thickness to chord ratio of 10% allowing for a section lift coefficient of 0.6 to be selected. When these selections were plugged back into the Korn equation gave a drag divergence Mach number of 0.8026 and a critical Mach number of 0.695. This drag divergence Mach number is good since it allows the SWAT design to remain below it at cruise, thus avoiding the drag increase that occurs following the drag divergence Mach number.

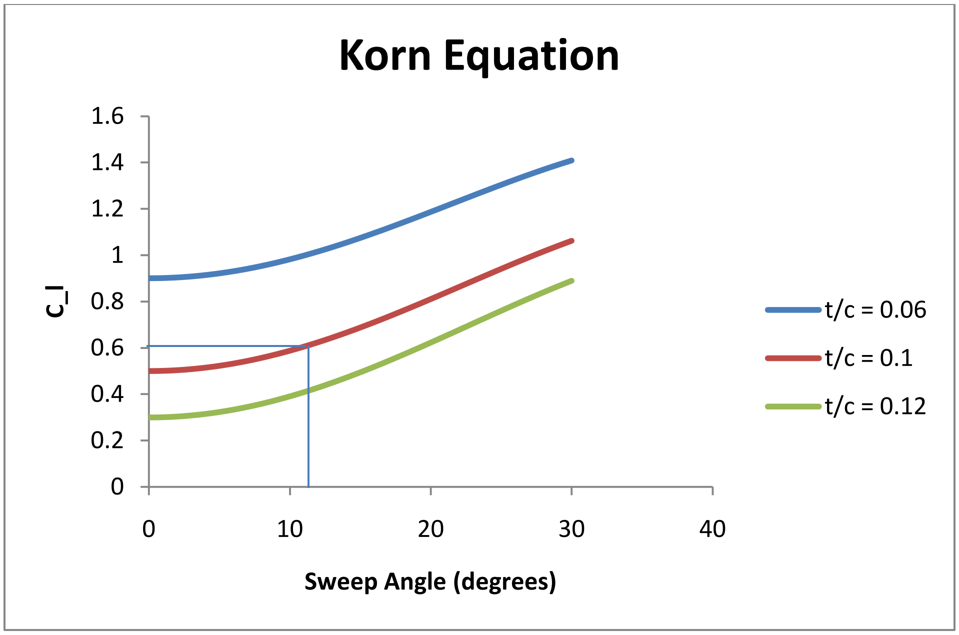


Figure 5.2 – Korn Equation Results

Slipstream Aerospace chose to use a NASA supercritical airfoil because they were designed to operate at transonic velocities while maintaining reasonable low-speed performance. The NASA SC(2)-0610 was selected for the main wing as well as the horizontal stabilizer because it met the requirements previously selected of 10% thickness to chord ratio and a section lift coefficient of 0.6. Figure 5.3 shows the airfoil cross-section.

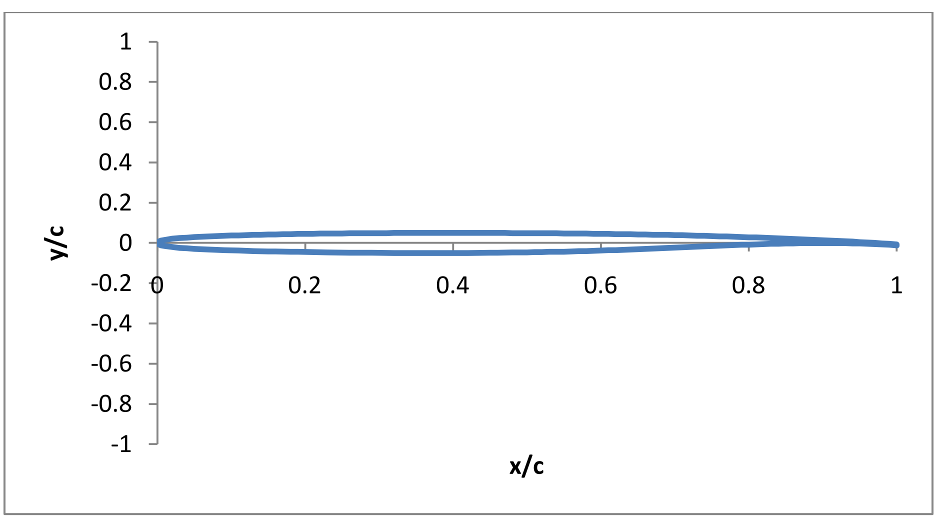


Figure 5.3 – NASA SC(2)-0610

For the control surfaces a symmetric airfoil was needed. For this purpose a NACA 0010 airfoil was selected for the ailerons and elevator. For the rudder and vertical tail a NACA 0012 airfoil was selected to provide the additional strength required by the T-tail as well as maintaining a symmetric airfoil. The sizing of these control surfaces will be discussed later on in the stability section. The airfoil was analyzed using xfoil. Figure 5.4 shows the coefficient of lift versus the angle of attack of the airfoil at takeoff, at a speed of Mach 0.2 and a Reynolds of 10^6. Figure 5.4 also shows that the angle of stall for the airfoil is approximately 15 degrees.

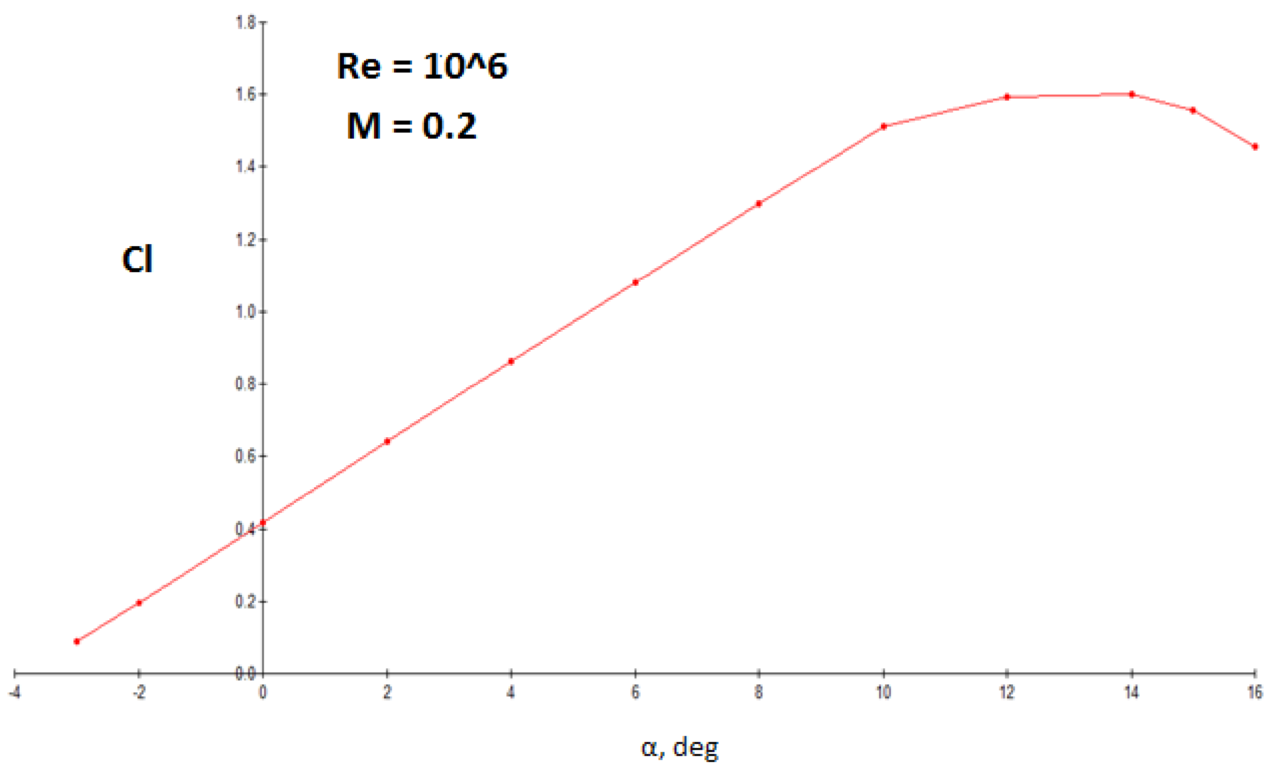


Figure 5.4 - Lift Curve for SC(2)-0610

5.2 High lift devices

According to the requirements the landing speed is 140 knots or less and from the performance calculations the takeoff speed was 140 knots. To be able to achieve this value high lift devices had to be used. Krueger flaps where used to increase the maximum angle of attack before stall. Krueger flaps were used because they will not interfere with the natural laminar flow. Krueger flaps are built in a way that there are no discontinuities over the wing along the wing chord when the flaps are retracted during cruise. Avoiding discontinuities along the chord reduces the thickness of the boundary layer thereby reducing the chances of having an early boundary layer transition. Figure 5.5 shows an example of an airfoil with a Krueger flap

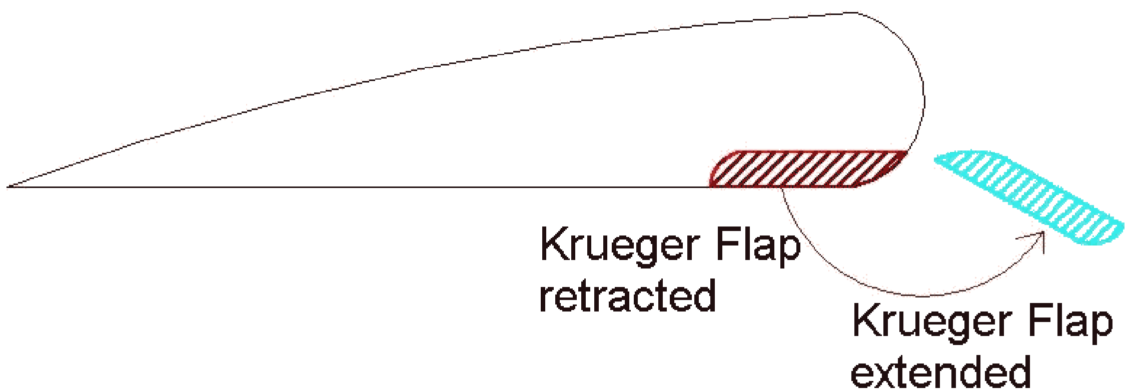


Figure 5.5 – Krueger Flap Assembly [18]

For flaps the single slotted flaps were used and the reason for this was because using single slotted flaps allowed the SWAT design to achieve the amount of lift needed during takeoff and landing as well as being able to meet the FAR requirements for commercial transport. Also single slotted flaps are simple flaps and cost less to build. The flaps cover 30% of the chord length. The flaps cover about 60% of the wingspan. Table 5.2 shows the coefficients of lift required at takeoff and landing.

Table 5.2 – Lift Coefficient Requirements

	Speed(Knots)	C_L required	C_{LMAX}
Takeoff	140	1.81	2.43
Cruise	529	0.4	1.8
landing	140	1.52	2.8

The coefficient of lift needed for cruise is about 0.4. And this lift coefficient was calculated for the airplane just after climb when it starts cruising and the only fuel used had only been used during takeoff and climb.

5.3 Drag analysis

5.3.1 Parasite drag

This drag was calculated using the friction drag code, the airplane was broken into different components and the skin friction drag coefficient was calculated for each component was calculated and these were then added together to get the total skin friction drag for the aircraft.

Table 5.3 shows the drag build up at takeoff and at cruise. At takeoff the drag due to the landing gear has been included.

Table 5.3 – Drag Build Up

Takeoff(Mach=0.2)	0.02032
Cruise(Mach =0.8)	0.01500
Landing(Mach=0.2)	0.02500

5.3.2 Induced Drag

This is the drag due to downwash and lift produced. Figure 5.6 shows how the induced drag varies with the change in the coefficient of lift.

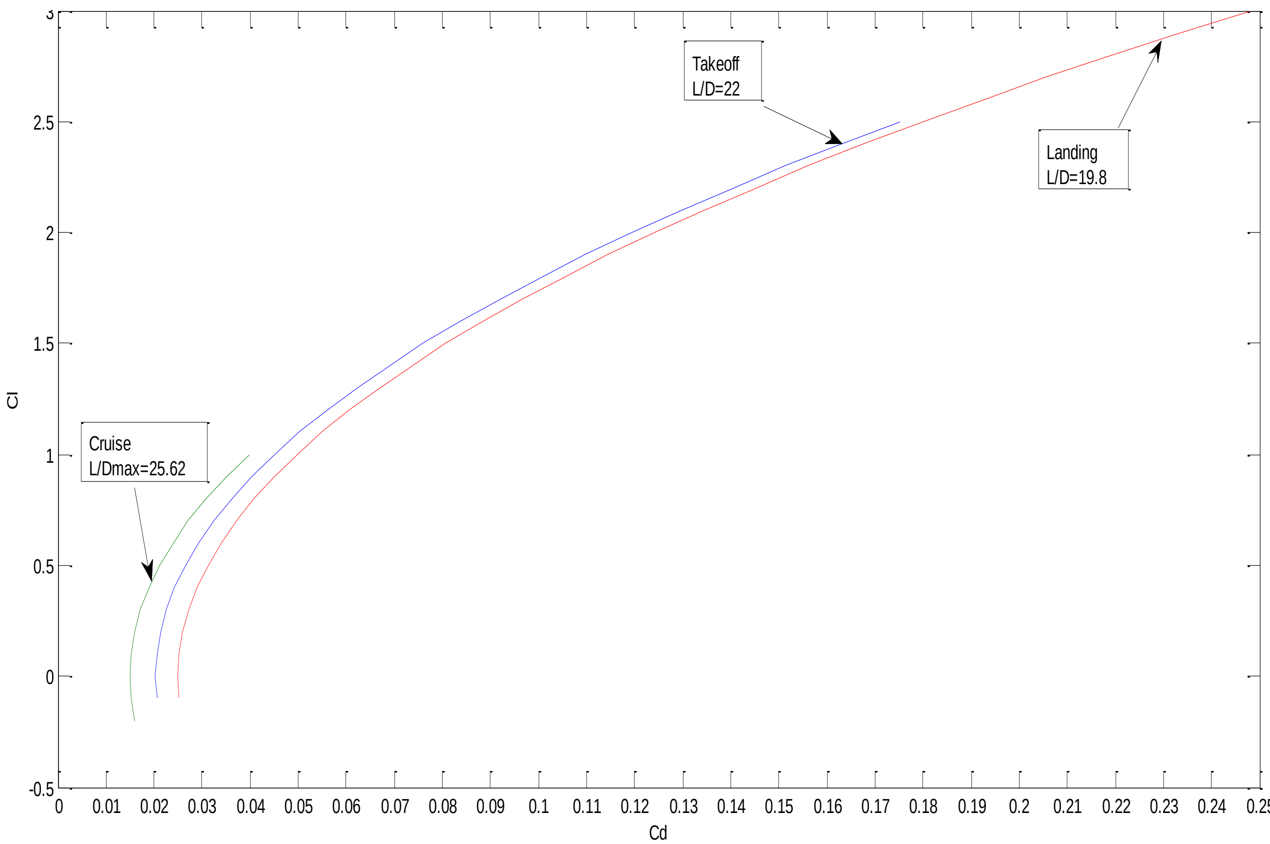


Figure 5.6 - Drag Polar at Cruise

Figure 5.6 shows that if the plane is cruising at a lift coefficient of 0.4 the drag coefficient will be about 0.0018. The Oswald efficiency factor was found using the idrag code.

5.3.3 Wave drag

This is the drag due to shockwaves in the transonic region, this drag is not significant until the drag divergence Mach number is reached, after the drag divergence Mach number is reached the drag rises quickly. Figure 5.7 shows the relationship between the Mach number and the drag.

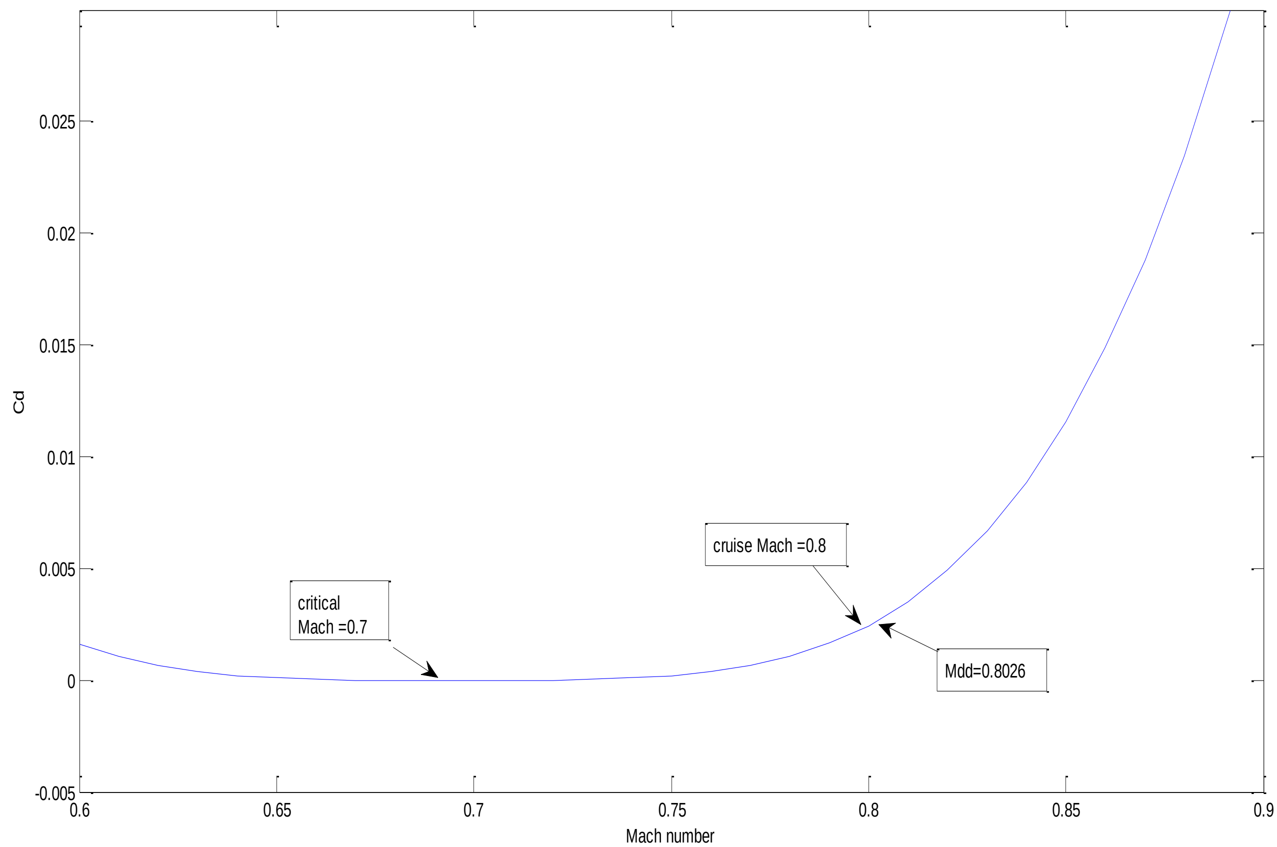


Figure 5.7 - Drag divergence

The critical Mach number is 0.695, the cruise Mach number is 0.8, and the divergence Mach number is 0.803. Figure 5.8 shows the drag build-up on the aircraft during takeoff, cruise and landing.

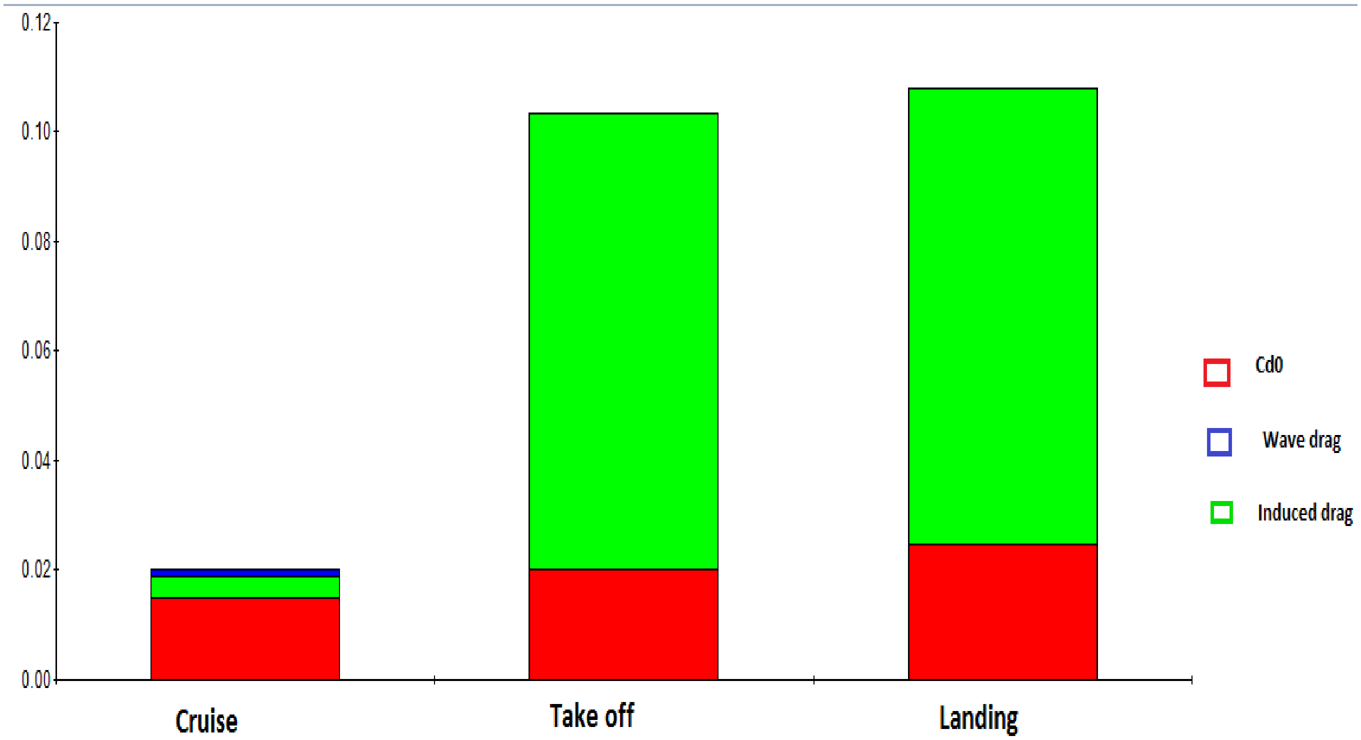


Figure 5.8 – Drag Build-up

6 Stability and Control

Slipstream Aerospace designed the SWAT to meet the specific requirements set by the FAA, FAR, MIL and the RFP. In the design process the SWAT was designed to have all the traditional control surfaces and a tail sized to meet all those requirements as well as the engine out condition. Some of the programs used to calculate the required stability and control data was the LDstab and TORNADO programs; these programs were used to find stability derivatives, engine out criteria and static margin. Specifically, they both were used to find stability derivatives, but the TORNADO program allowed for the determination of the neutral point location, while the LDstab program determined the engine out criteria. The SWAT design was evaluated at the critical condition for each of the requirements; for the engine out requirement it was evaluated at sea level for takeoff conditions, and for the neutral point location it was evaluated at maximum altitude at the cruise Mach number of 0.80. The control surfaces were sized to meet and add a margin of safety to each requirement to produce the required pitch, roll and yaw rates. The flaps and their sizing were discussed in the Aerodynamics section to meet the required maximum lift to drag ratio as set in the RFP.

6.1 Vertical and Horizontal Tail Analysis

The vertical tail was designed to provide enough of an available yaw coefficient to exceed the required yawing coefficient of the aircraft. The vertical tail is located on top of the fuselage and 60.9 feet from the apex of the wing to the apex of the vertical tail. The vertical tail has a root chord of 13 feet and a tip chord of 9 feet. The total area of the vertical tail is 245.45 square feet with an aspect ratio of 2.155. The vertical tail was positioned and sized to achieve the engine out requirement as well as provide a good static margin for the SWAT design.

The horizontal tail was designed to achieve and surpass the industry standard of $7°/s^2$ pitch angular acceleration for similar aircraft. The horizontal tail was placed on top of the vertical tail at 125.2 feet from the wing apex. The horizontal tail has an area of 375 square feet, root chord of 9 feet and a tip chord of 6 feet; the reason for this high taper ratio was because of the low leading edge angle of 12°. A T-Tail was selected to provide clearance from the turbulent flow downstream of the wing, which will decrease the size of the horizontal tail. One downside was that it required reinforcing the vertical tail structurally. Another downside to this is that there are now two trim points, the second one being unrecoverable, and our solution was to have an angle of attack limiter implemented to prevent the aircraft from ever achieving that angle of attack. The limiter will be set to a maximum of 25° angle of attack to prevent the aircraft from achieving an angle of attack of 28° which is approximately the second trim angle.

The specific value of the required yaw coefficient was found using the method described in Grasmeyer's research.[14] The available yaw coefficient was found under the FAR 25 requirements; which is as follows one engine has failed at a velocity of $1.2V_{stall}$, the other engine will maintain a maximum thrust of 26,300 lbs and the bank angle will not exceed 5°. The available yaw coefficient was found using the LDstab program.[14] The output including both the available and required coefficients can be found in Table 6.1.

Table 6.1 – Engine Out Requirement and Performance

β	-0.2346°
ϕ	5°
δ_a	4.4017°
δ_r	20°
C_{Nreq}	0.015906
C_{Navail}	0.0594

6.2 Neutral Point

The neutral point of the SWAT design was found using the Tornado's VLM [15], and was modeled with 32 panels chord wise and 32 panels span wise for the main wing, vertical tail and horizontal stabilizer. A model of the main wing, vertical tail and horizontal stabilizer can be seen in Figure 6.1. The neutral point was calculated to be 27.54% of the MAC and the main wing was adjusted to provide a static margin of 10%. The center of gravity travel and neutral point is shown in Figure 6.2. Which shows that as the fuel is burned and the center of gravity moves closer to the neutral point it remains safely at a static margin of 7.6% at the point of no fuel. Table 6.2 shows the exact values of the center of gravity and relative static margin.

Table 6.2 – Center of Gravity Travel Locations

Condition	Center of Gravity	Static Margin
Full	58.7 ft	10%
No Fuel	59.0 ft	7.6%
No Payload	57.9 ft	16.4%
Empty	57.8 ft	17.2%

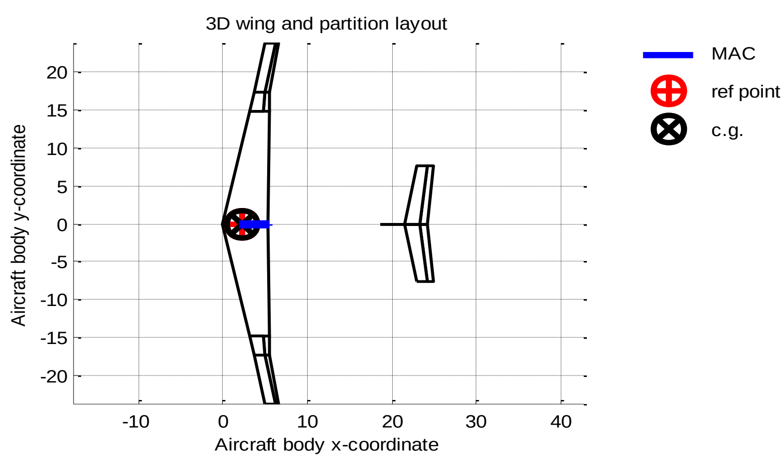


Figure 6.1 – TORNADO Wing and Partition Layout

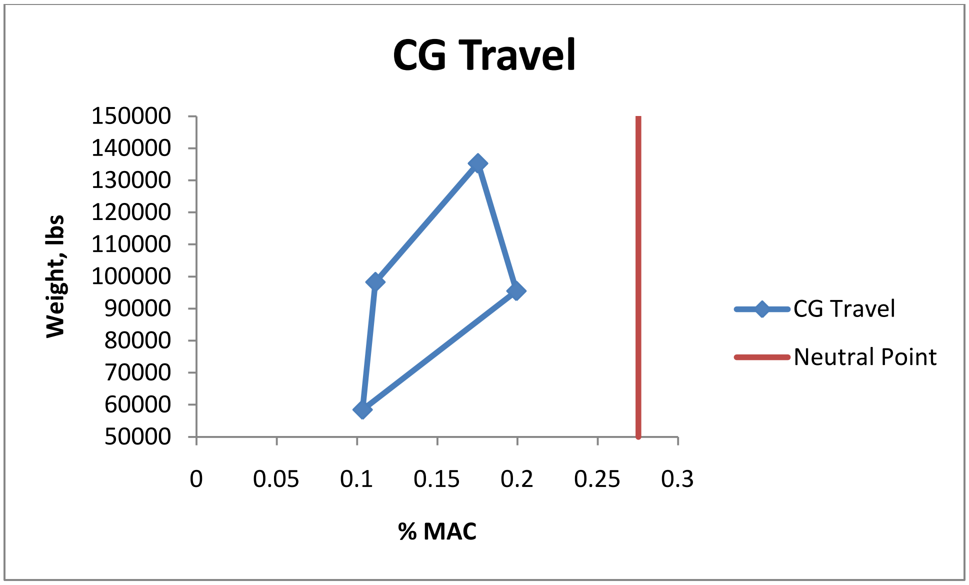


Figure 6.2 – Center of Gravity Travel with respect to the Neutral Point

6.3 Control Surface Sizing

The control surfaces were sized according to their corresponding FAR, FAA or MIL-STD requirements. The MIL-F 8785B roll requirement for a class III aircraft is such that the aircraft in question must be able to roll 30° in 1.5 seconds. The ailerons were sized to not only meet, but to exceed this requirement. The ailerons were sized to be 25% of the chord length and 30% of the half span on both sides of the wing. They were located right before the joint on the outer portion of the wing where the trailing edge angle becomes 10°. The calculated roll time is shown in Figure 6.3, but the exact time to roll 30° was found to be 0.98 seconds. The detailed requirement and results are shown in Table 6.3.

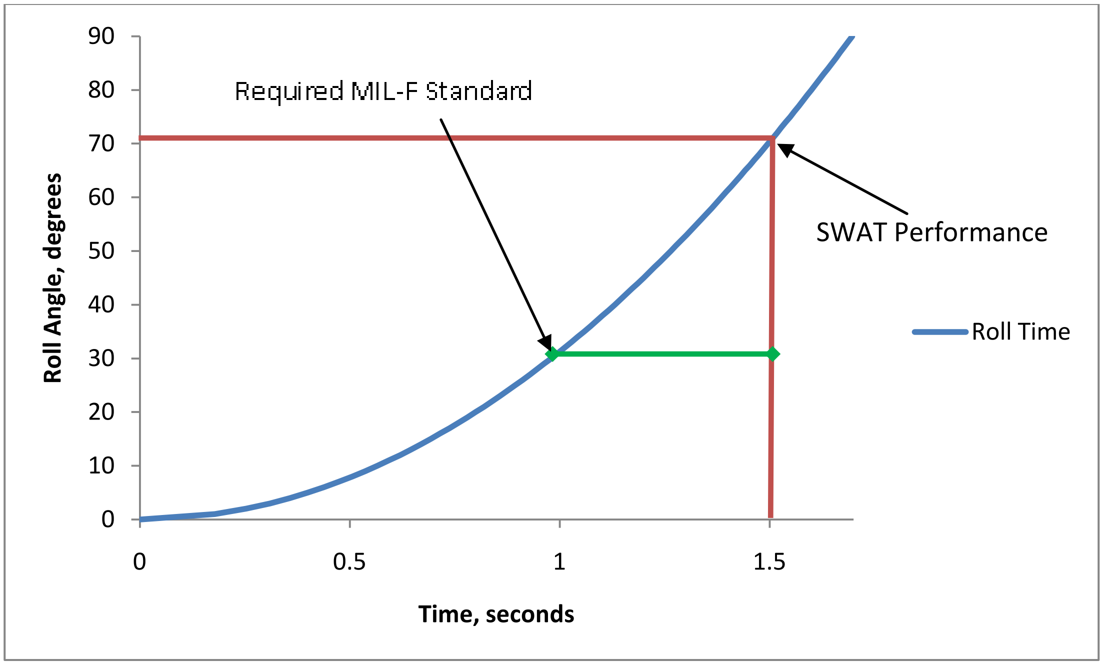


Figure 6.3 – SWAT Roll Performance

The elevator was sized to achieve at least a 7°/s^2 pitch angular acceleration, as this comes from the value used for most class 3 aircrafts. The actual value for pitch angular acceleration was found to be 11.3°/s^2. The elevator used for this calculation was 30% of the horizontal tail chord length and 80% of the span allowing for a gap where the rudder would interfere with the elevator.

The rudder was designed so that it met and exceeded the engine out requirement. The rudder was sized to be the entire length of the span and 30% of the chord length. The C_{Nreq} was found to be 0.015906 and the C_{Navail} was found to be 0.0552. The excess is useful so that in non-ideal conditions the rudder will still be able to perform as needed. These results were shown earlier in Table 6.1. The results for all the control surfaces and their corresponding requirements are shown in Table 6.3.

Table 6.3 – Stability and Control Requirements and SWAT values

Control Surface	Achieved Value	Requirement
Aileron	70.3° in 1.5 seconds	Roll 30° in 1.5 seconds
Elevator	$11.3°/s^2$	$7°/s^2$ pitch angular acceleration
Rudder	$C_{Navail} = 0.0552$	$C_{Navail} > 0.015906$

6.4 Dynamic Analysis

The Short period damping ratio, natural frequency and phugoid damping ratio requirements were found from the MIL-STD requirements for a Category B Class 1 aircraft. The performance of the SWAT design for these specific categories was found using the methods laid out in Etkin and Reid. [16] The SWAT design fit the constraints given to it under the MIL-STD requirements; these results are shown in Table 6.4. These values were tested at the cruise Mach number of 0.8 as the short period and phugoid modes depend heavily on the velocity of the aircraft. The control derivatives for the SWAT design are shown in Table 6.5.

Table 6.4 – Dynamic Mode Requirements and SWAT Performance

		MIL-STD Cat. B Level 1 Requirements	SWAT Performance
Short Period	Damping	$0.3 < \zeta_{SP} < 2.0$	0.759
	Natural Frequency (rad/s)	0.8 rad/s < ω_{sp} < 2.0	1.458
Phugoid	Damping	$\zeta_{PH} > 0.04$	0.1515

Table 6.5 – SWAT Stability Derivatives

Cruise Mission Station	**SWAT**
$C_{y\beta}$	-0.632
$C_{N\beta}$	-0.126
$C_{L\beta}$	-0.04
C_{Yr}	0.0061
C_{Nr}	0.0012
C_{Lr}	0.003
C_{Lp}	-0.0927
C_{Np}	-0.0316

7 Performance

7.1 Takeoff characteristics

In compliance with the RFP, takeoff has to be at most 8200 feet. In order to calculate takeoff characteristics, certain aspects must first be defined. Takeoff length is a function depending on the wing loading at takeoff, the thrust to weight ratio, the lift coefficient at take off and the density ratio. However, before one can solve for a concrete value for takeoff, each parameter needs to be found. Wing loading is found from takeoff condition weight divided by wing planform area. The thrust to weight ratio is found by taking maximum thrust and dividing it by the takeoff weight. Next, the maximum lift coefficient at take off needs to be found. This is found by using the sweep angle and Raymers.[1] Once this value is found, the density ratio needs to be found. This is done by the following equation:

$$\sigma = \left(\frac{\rho_{TO}}{\rho_{SL}}\right) \qquad (27)^{[1]}$$

Where: σ= density ratio

ρ_{TO} = density at takeoff

ρ_{SL} = density at sea level

This is done by taking the air density at takeoff altitude divided by the density at sea level. For the purposes of the values calculated, the take off altitude is assumed to be at sea level, thus making the density ratio equal to one. After these parameters have been calculated the last entity that is significant is the take off parameter. This value is solved for using Equation 5.9 from Raymer's text and is as follows:

$$\frac{W}{S} = (TOP)\sigma C_{L_{TO}}\left(\frac{T}{W}\right) \qquad (28)^{[1]}$$

Where: $\frac{W}{S}$ = thrust to weight ratio

TOP = Takeoff parameter

σ= density ratio

$C_{L_{TO}}$ = Lift coefficient at take off

$\left(\frac{T}{W}\right)$ = Thrust to weight ratio

The value of the takeoff parameter is then taken and compared to a graph found in Chapter 5 of Raymer's book.[1] This method is used to calculate both of the takeoff distances for the SWAT and HAWC aircrafts. Data for takeoff is shown in Table 7.1.

7.2 Stall and Takeoff speeds

An important part of takeoff characteristics is finding the values stall and takeoff velocity. In order to find takeoff velocity, the stall speed must be first calculated. Stall speed is found as a function of the density, maximum lift coefficient and the wing loading. For the purposes of the data calculated in this section, density is assumed to be the density at sea level which is 0.00237 slugs/ft^3. Maximum lift coefficient is found from Figure 7.1 and the wing loading is found from dividing the takeoff weight divided by the wing planform area. The equation is as follows and is derived from Equation 5.6 from Raymer's book.

$$V_{stall} = \sqrt{\frac{2W}{\rho S C_{L_{max}}}} \quad (29)$$ [1]

Where: V_{stall} = Stall velocity

$\frac{W}{S} =$ Thrust to weight ratio

$\rho =$ Density at altitude

$C_{L_{max}}$ = Maximum lift coefficient

Once the stall velocity is found, the takeoff velocity can be found. Aircrafts generally take off at 1.1 times the stall speed. The equation is as follows:

$$V_{TO} = 1.1V_{stall} \quad (30)$$

The values found in the previous sections are shown in the following table:

Table 7.1 - Takeoff characteristics

	HAWC	SWAT
Total Thrust (lbf)	62400	52600
S (ft^2)	1550.08	1454.91
b (ft)	125.4	140
Sweep (deg.)	30	12
TOGW (lb)	185990	174590
Clmax	2.75	2.93
Vstall (mph)	130.83	133.28
Vtakeoff (mph)	143.91	146.61
Clmax TO	2.27	2.19
W/S	119.98	120
T/W	0.336	0.301
Takeoff paramater	157.36	181.87
Takeoff distance (ft)	7000	7300

Table 7.1 shows that SWAT has a stall speed of 133mph. This low stall speed is due to the high wing planform area. A lower stall speed entails a lower takeoff speed for an aircraft.

As a result of a lower takeoff speed, the takeoff distance will be reduced. Therefore, since SWAT's stall speed is higher, the takeoff distance is greater than that of HAWC's. By calculating the stall and takeoff speed characteristics a takeoff parameter of 181.87 is found for SWAT which translates to a takeoff distance of 7300 feet. A takeoff distance of 7300 feet is a good value to have as the RFP calls for 8200 feet. This allows an extra 900 feet of safety for the aircraft.

7.3 Mission Profile

Since SWAT is designed to be a commercial aircraft, the mission profile is similar to that of every commercial aircraft. This mission profile is shown in Figure 7.1:

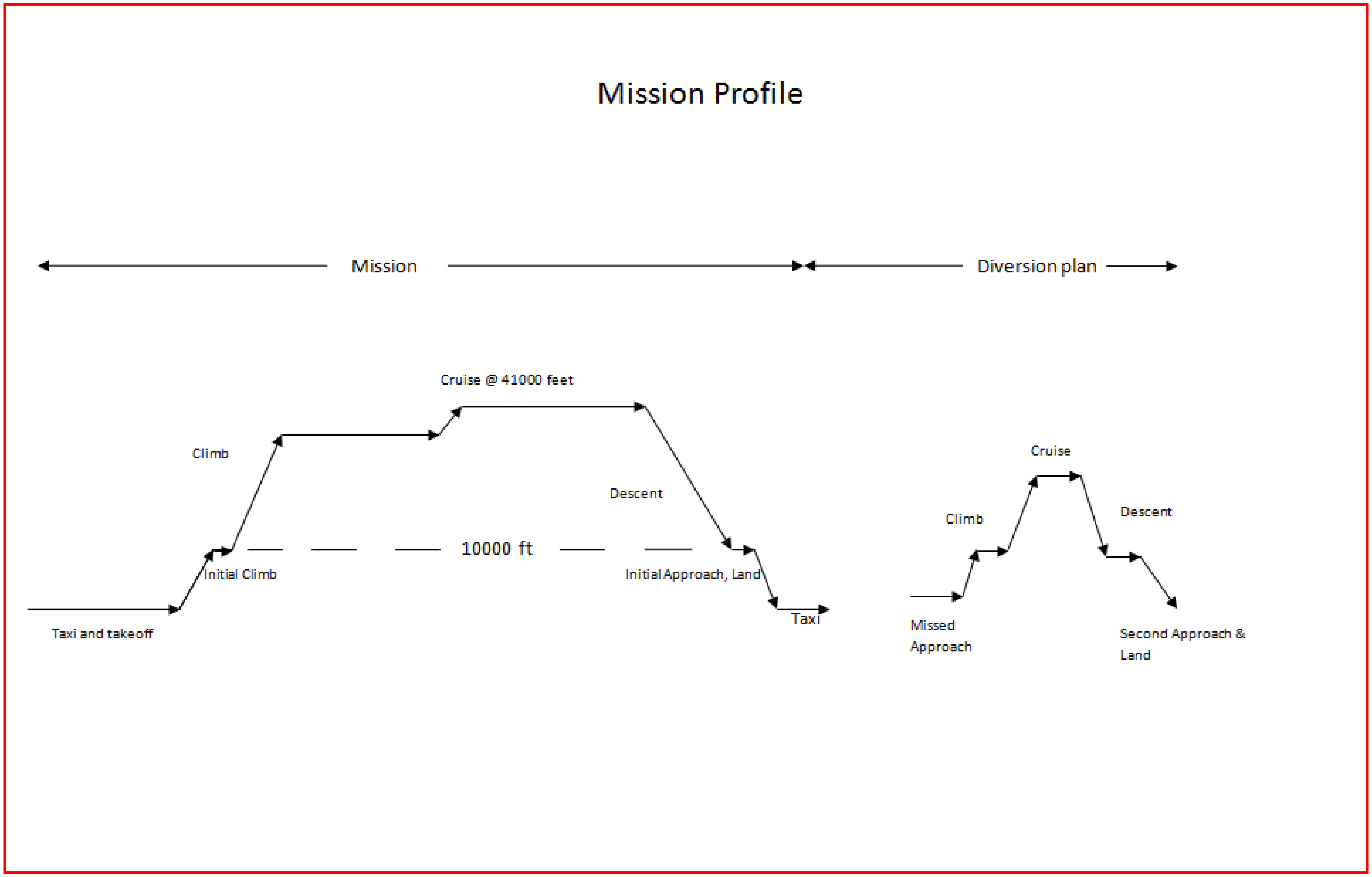


Figure 7.1 - Mission Profile with included diversion plan

Figure 7.1 shows that the mission profile is divided up into two main parts, the mission and the diversion plan. The mission accounts for all of the normal parts of a flight while the diversion plan accounts for a missed approach or a diversion. The mission portion of the mission profile shows a level off in altitude at 10,000 feet. This is because there a flight regulations which have speed and noise regulations at this altitude. It is the same for the initial approach at 10,000 feet. The diversion portion has the same regulations at 10,000 feet and since the flight time is less than that of the actual mission, the cruise level is significantly lower than the mission altitude of 41,000 feet.

8 Structural Analysis

The SWAT is made of different materials that enable it to gain an advantage to similar aircraft in the areas of weight savings and targeted structural integrity. Key to the weight savings is the by and large use of carbon composites, which posses similar strength properties yet lower densities.

The analysis of the aircraft structures focuses on three areas: (1) the materials used to build the major components of the aircraft, including a high percent carbon composite materials, (2) the effect targeted structural integrity areas with the use of a strut to alleviate the bending moment at the wing root, and (3) the required overall structural integrity of the aircraft from gust loads and the maneuvering limit loads (V-n diagram).

8.1 Materials

The following sections discuss the main materials used in each of the major components of the aircraft structure. A key feature of the SWAT is the use of carbon laminate and sandwich composite materials in the skin that reduces the overall weight compared to a Boeing 737, allowing for allocation for extra components or extra cargo.

8.2 Control Surfaces and Leading Edges

The control surfaces and leading edges located in the wing have high thermal conductivity for de-icing heating operations. An Aluminum 2024 alloy is employed in all control surfaces and leading edges, a material that posses high conductivity and low cost compared to carbon composites used in other areas. This allows for inexpensive repair and maintenance of the control surfaces, especially for the leading edges in case of bird strikes. The control surfaces are covered with the heating mats discussed in the Aircraft Systems section.

8.3 Fuselage and Skin

The fuselage and skin need to carry shear and pressure forces. A carbon composite laminate is able to hold these forces. The carbon composite laminate is a carbon reinforced epoxy polymer that covers the entirety of the skin, except for the certain skin areas where lower density fiberglass is employed. These areas are the nose cone (to reduce for radar interference), wing-fuselage skin (where most of these loads are already carried underneath by the bulkhead components), and the landing gear housing, which carries minimal shear and pressure forces.

8.4 Longerons, Stringers, Bulkhead, and Strut

The longerons and stringers carry axial loads, while the bulkhead carries the forces from the wing, landing gear, and strut, which carries the bending moment of the wing lift load. These materials need to have a high life cycle and also light. The strut is constructed from titanium alloy AMS 4920, is vital to the reduction of bending moments at the wing root and is able to carry heavy loads, and the titanium allows for greater structural strength.

8.5 Wing Box

The wing box employs all new carbon reinforced epoxy polymer sandwich composite that provides a weight savings with the similar rigidity of traditional aluminum and titanium alloy boxes. This composite uses an epoxy matrix and woven carbon fibers that can hold loads in different directions where needed, unidirectional or multi-directional.

8.6 Strut Design Analysis

The use of a strut is advantageous because it reduces the bending moment at the wing root. The wing box is analyzed as a cantilever beam with a distributed lift load and a point force of the strut.

Shear and bending moment diagrams of a wingbox with and without a strut show the difference of bending moment at the root of the wing. Also, an optimal position of the strut is found to be at the 75% length of the wing span, taking into consideration where the mass for a strut is minimized and the reduction of bending moment is maximized.

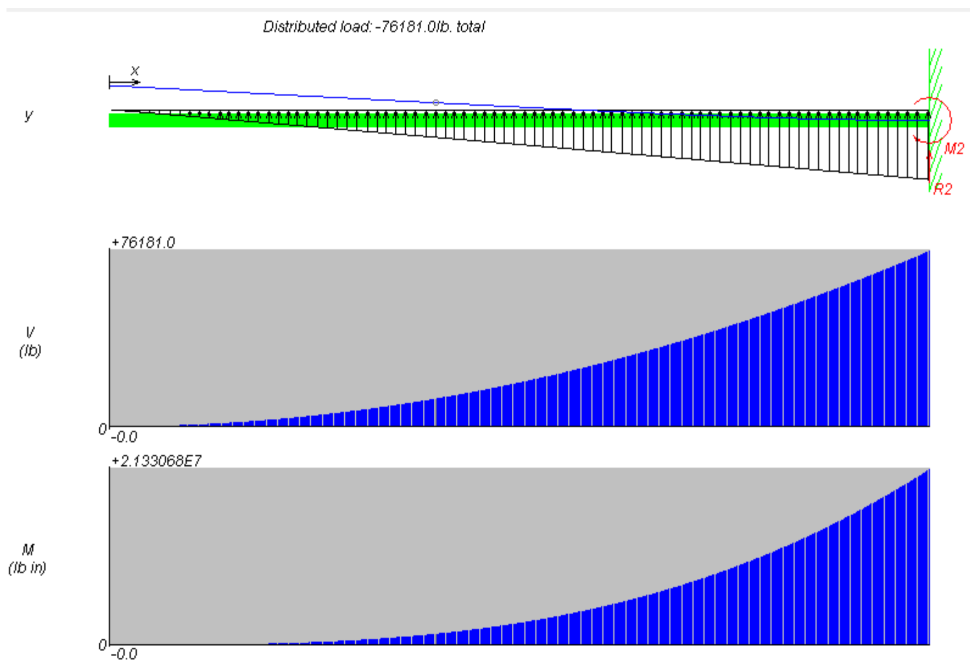


Figure 8.1 - Wingbox without strut

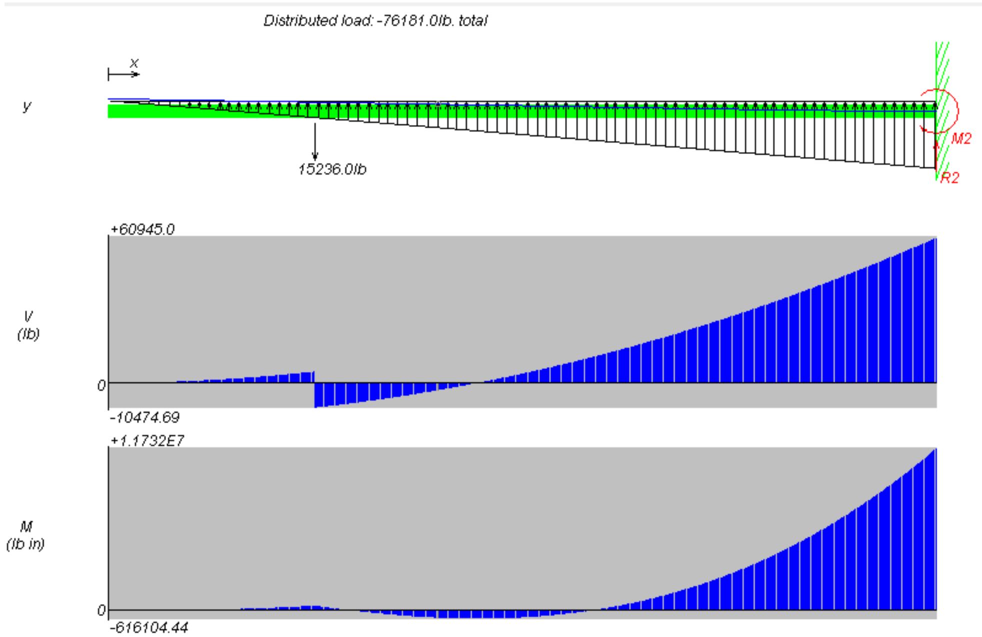


Figure 8.2 - Wingbox with strut at the 75% length of span

The reduction of the bending moment at the wing root is significant: a strut at the 75% length of the span reduces the bending moment by 9,600,000 lb-in, or 30%. The strut does more than reduce the bending moment, but it also decreases the overall weight of the plane by reducing the thickness of the wing structural members. Since the bending moment of the wing is directly proportional to its weight by integrating the bending moment graph, an idea of the wing weight is obtained. A combination of different placements along the span indicates that the most weight savings occurs at the 75% span.

8.7 V-n Diagram

In order to find the maneuvering limit loads including loads at gust conditions, a V-n diagram is created following the requirement of the Military Specification 1-8861b[26], with limit load factors of +2.5 and -1.0

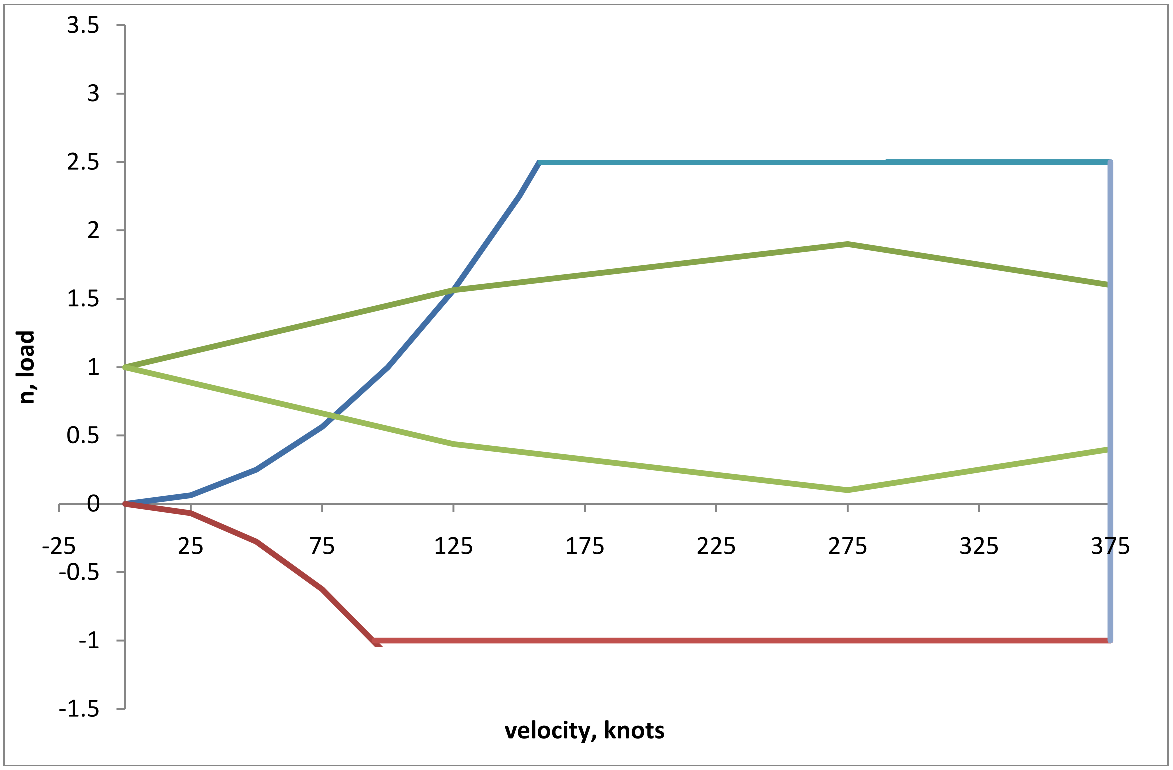


Figure 8.3 - V-n Diagram showing positive loads (blue), negative loads (red) and gust loads (green)

9 Aircraft Systems

The SWAT aircraft is slated to be unveiled in 2020 as a technically superior and cost effective air transport vehicle. Therefore, a number of new technologies have been incorporated into the systems of this aircraft including non-hydraulic flight control systems, improved cabin integration, and no-bleed wing icing protection, among others. However, many of the systems are modeled after those that made aircraft like Boeing's 737 and Airbus' A320 the preeminent commercial airliners in recent history.

9.1 Flight Control System

Due to the necessity for increased lift and reduced weight, the SWAT aircraft will not contain a high weight hydraulic system. Instead, a number of electro-hydrostatic actuators (EHAs) will be present to deflect primary and secondary control surfaces. For redundancy, there will also be a set of electro-backup hydrostatic actuators (EBHAs).

In present aircraft, a fly-by-wire system is used to replace the manual control of an aircraft with an electronic interface. Once the pilot tells the aircraft what he wants it to do (whether using a computer or control stick) the information is converted into electronic signals and transmitted to the flight control computers which, in turn, determine how to move the actuators to achieve the desired flight response. The SWAT, however, will be equipped with a new technology called "fly-by-light", or "fly-by-optics". The data being transferred and response from the actuators will remain the same, but using a fiber optic cable allows for a very high rate of transfer and therefore quicker aircraft response times. Fiber optics are also immune to electromagnetic interference while current fly-by-wire systems are not. [6]

The SWAT will require two different kinds of EHAs: linear actuators for the primary control surfaces and rotary for the secondary. Linear actuators will control the ailerons, rudders, and elevators. Rotary actuators are needed to extend and retract flaps, slats, and air brakes.

9.2 Electrical System

The electrical system on the SWAT will be similar to that of the 737. It will include a standard auxiliary power unit (APU), lead acid battery, and two backup generators. The Honeywell APU will primarily be used to start the twin engines without any additional ground support. In order to do this, the APU is started by a small electric motor which is in turn powered by a battery. Once the APU has accelerated up to full speed, it is able to generate enough power to turn an electric generator and start the engines. The APU will also be used to power up systems in pre-flight checks (before the engines are started) and to heat/cool and ventilate the cabin for comfortable passenger boarding. [8]

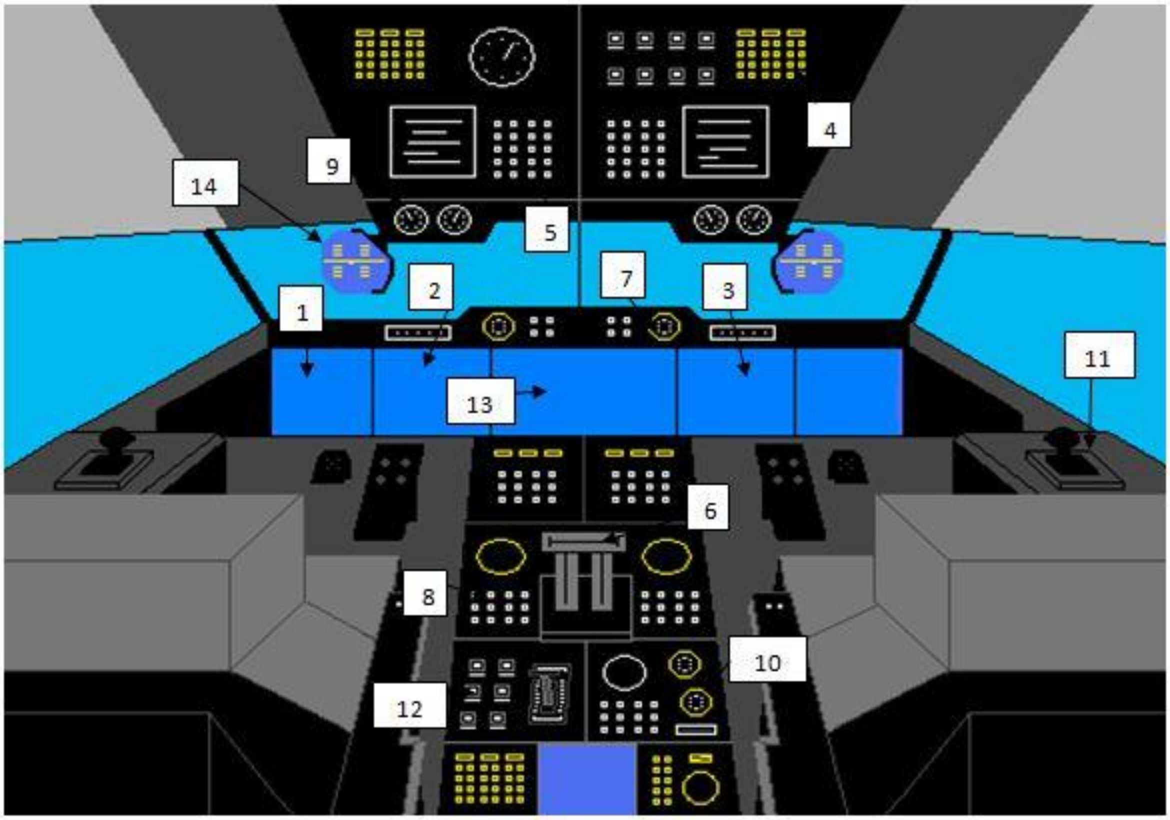
The lead acid battery is used as a failsafe in the event of an APU malfunction; it will provide emergency DC power to the vital flight controls. Once the aircraft is in flight, the two backup generators are used to power the aircraft systems. [7]

9.3 Cockpit and Avionics

Unlike many other aspects of the SWAT, the cockpit and avionics systems are modeled after those present on a military aircraft; namely an Airbus A400M. This layout was chosen because of the upgrades installed to improve functionality and increase safety. The Honeywell Primus Epic Integrated Avionics system was chosen because it meets all the current requirements while providing improved situational awareness and increased system flexibility for the future aerospace market.

The cockpit will be equipped with liquid crystal flat panel displays of various sizes which allows for a large amount of data to be gathered in one location. Information concerning communication, navigation, systems management, and weather can all be displayed in a unique user-designed way that is most comfortable for the pilot. The interactive nature of this system is much like that of a home computer; on-screen point and click functionality along with drop down menus make this an easy and familiar system to operate. The system is also software-based which means that (again like a home computer) the suite can be easily interchanged with any future system updates such as communication, navigation, and surveillance/air traffic management products.

A few other notable features on the avionics system is Honeywell's patented INAV which is the industry's first interactive navigation system that allows the simultaneous display or terrain, traffic, airspace, and airway navigation aids. The system also includes a fully digital, fully integrated autopilot and auto throttle as an integrated ground proximity warning system. The use of a heads-up display (HUD) provides pilots with improved situational flexibility especially during reduced-visibility takeoffs and landings. An example of the SWAT's cockpit layout can be seen in Figure 9.1 [9]



1	Primary Instrument Display	8	Autopilot Controls
2	Navigation Display	9	Heading and Altimeter Gauges
3	Engine Controls	10	Radio Controls
4	Fuel Controls	11	Control Stick
5	Environmental Controls	12	Landing Gear Controls
6	Throttle	13	Additional Display Screen
7	Fuel Gauges	14	Heads Up Display

Figure 9.1 – Labeled Cockpit Layout

9.4 Landing Gear

To keep this aircraft current for future markets it will include the same landing and braking system that airbus is currently developing for their A320. This landing and braking system is a self powered braking system. The system uses generators coupled to one of the wheels on the landing gear, when the wheels spin during takeoff, the generators produce electrical energy which is then stored once the aircraft is in the air the stored kinetic energy is then used to retract the gears. During landing the gravity assisted free falling landing gear would internally generate power via the damping system and that power would then be used to spin the wheels. On the ground some of the stored kinetic energy is used for the braking system. The benefits of this scheme include cutting down the number of redundant cable and pipe runs between centralized electric power generators, typically driven by the engines.

Also in addition to reducing the weight of the aircraft and scavenged power from the engines, a localized regenerative system requires less maintenance and is less vulnerable to damage along the considerable lengths of cable and pipe runs. Also, this system will reduce the amount of fuel burnt during landing.

The landing gear configuration was modeled after the BAE-146; a similar high wing transport aircraft. A tricycle undercarriage was used consisting of two nose gear tires which retract forward and four main gear tires located just aft of the center of gravity that retract into the sponsors on the belly of the aircraft.

The positioning of the landing gear is primarily determined by the desire to keep the aircraft stable during certain maneuvers like taxiing, landing and taking off. The aircraft will be in no danger of rolling or tipping over. So the location of the landing gear is mostly affected by the center of gravity.

The length of the landing gear is set so that the tail doesn't hit the ground on takeoff or landing. This is measured from the wheel in the static position assuming an aircraft angle of attack for landing which gives about 90% of the maximum lift. This turns out to be from about 10-18 degrees for our aircraft.

The tipback angle is the maximum aircraft nose-up attitude with the tail touching the ground and the strut fully extended. To prevent the aircraft from tipping back on its tail, the angle off the vertical from the main wheel position to the center of gravity should be greater than the tipback angle.

A poor location for the retracted gear can cause a lot of problems in designing an aircraft it could increase the weight of the plane or increase the drag by a big factor. So it is important to have a good position for the gear to retract into whilst the aircraft is still in the air. It was decided to go with the conventional main-landing-gear retracted position which is in the oversized pod on the belly of the plane due to the lack of a wing-fuselage junction. The landing gear configuration can be seen in Figures 9.2 and 9.3.

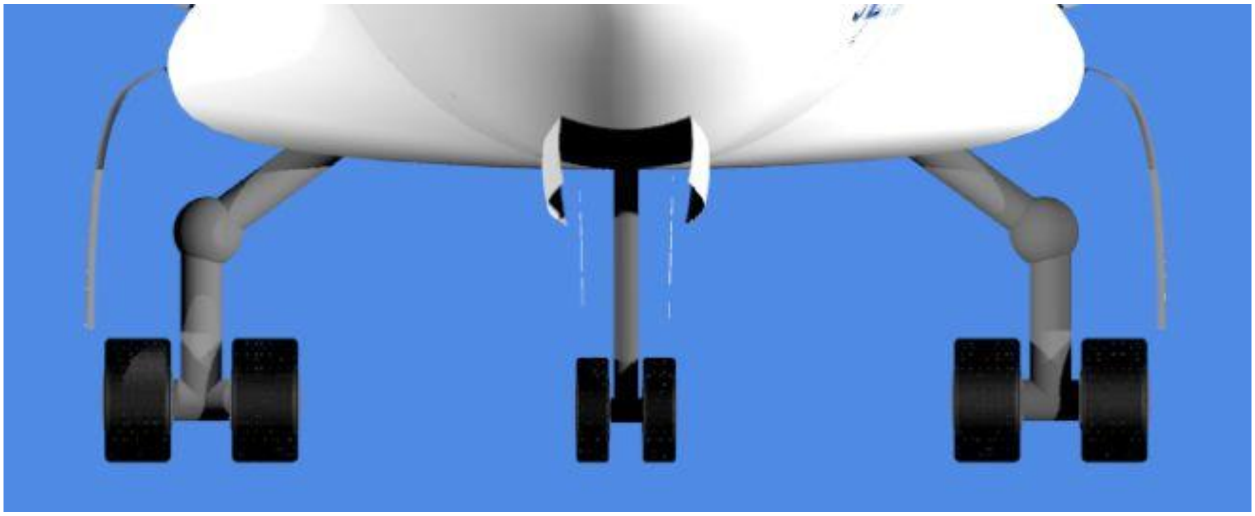


Figure 9.2 – SWAT landing gear configuration.

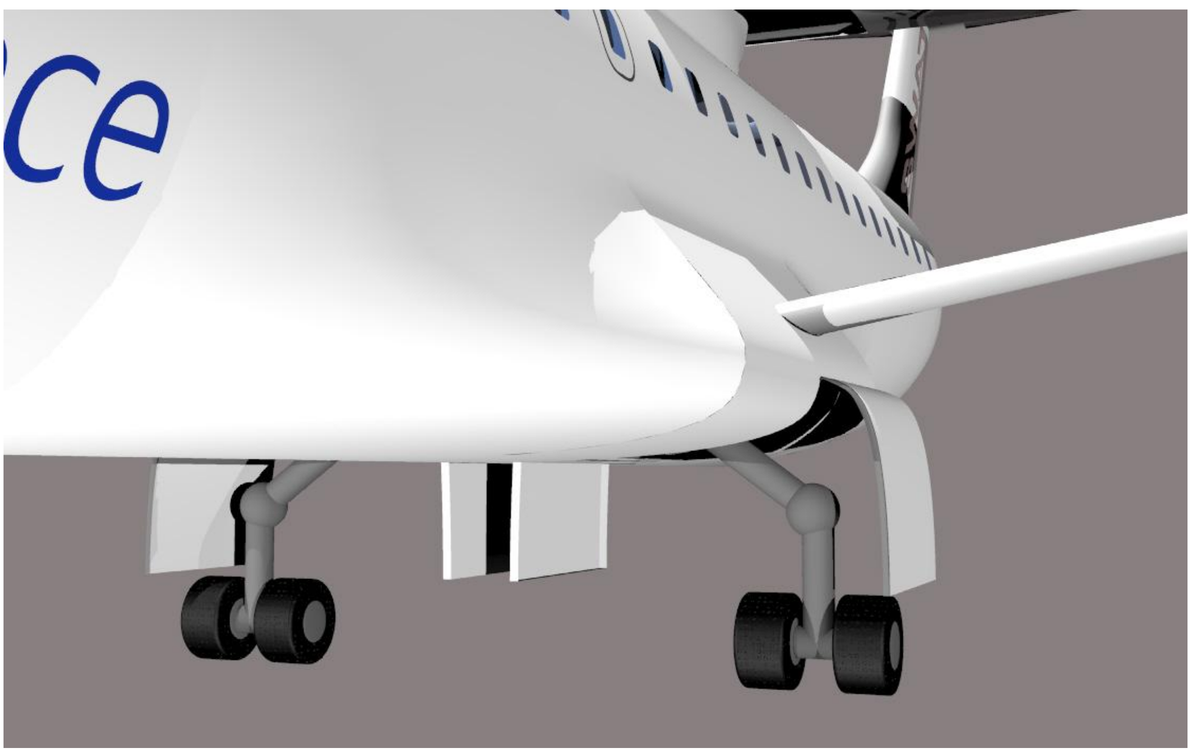


Figure 9.3 – Alternate view of SWAT main landing gear configuration.

9.5 Cargo System

The cargo loading system was designed based on existing 737 layouts and the RFP. The requirement is for a total of 1240 ft^3 of cargo space which means approximately 7.1 ft^3 per passenger (on a full flight). The system includes two areas of storage: overhead containers along the inside of the fuselage for which passengers have access to as well as a lower compartment for which there are two cargo doors for loading and unloading (forward and aft). The overhead containers and the lower compartment each consist of approximately half (or 620 ft^3) of the total storage space available.

The lower compartment containers are manufactured by a company called VRR Air Cargo Equipment. VRR supplies many Boeing and Airbus aircraft (among others) with specifically designed compartments to solve various cargo needs. The specific containers used for the SWAT are VRR's AKH series which can be seen in Figure 9.3. These containers were originally designed for Airbus' A319, A320, and A321 as a full width lower deck container for narrow bodied aircraft such as the SWAT. Each container will be approximately 105 ft^3 which means that a total of six will be needed to accommodate storage requirements for the lower compartment. [10]

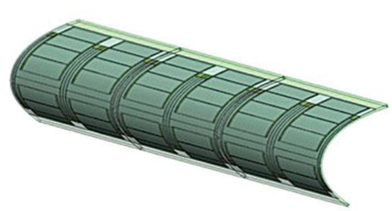
Figure 9.4 - SWAT lower compartment cargo container. [29]

Perhaps the most important characteristic of the lower compartment storage, besides being able to stow cargo, is its ability to contain a fire without endangering the safety of the rest of the aircraft. The hold is equipped with fire and smoke detection which notifies the cockpit as well as extinguishing capabilities in the case of a fire. [7]

9.6 Wing Ice Protection System

One of the easiest ways to disrupt the lift generation on an aircraft is to make the wing surface irregular rather than smooth. The most common way for a wing surface to become irregular is through icing; a layer of ice even 1 mm thick can be enough to destabilize an aircraft in-flight. The SWAT design will employ a new technology developed by GKN Aerospace (located in Redditch, U.K.) which is also being installed on the new Boeing 787 Dreamliner. This new system works by spraying liquid metal onto a fiber fabric mat located on the leading edge of the wing. The liquid metal acts as an electrical conductor, transferring heat to the wing skin.

The spray on metal is first embedded into what GKN calls a “heater mat”. The heater mat is a cured, multi-ply composite structure of carbon and glass fiber. Once the spray on metal is applied to the heater mat, it is shaped to fit the trailing edges of the SWAT wings. The heater mat operates over a temperature range of 45°F to 70°F. Figure 9.4 shows a photograph of a heating mat to be attached to the surfaces of the aircraft most prone to icing.



http://www.google.com/imgres?imgurl=http://www.compositesworld.com

Figure 9.5 - Example of heater mat located on wing leading edges.

These mats will be applied to the leading edges of the wings, the horizontal and vertical tails, as well as the engine cowlings. The application of GKN's heater mat system for de-icing eliminates the need for on-ground anti-icing as well as in-flight bleed air systems. The lack of bleed air ducts will also help to reduce noise and increase stability of the aircraft. [11]

9.7 Environmental Control and Emergency Systems

The SWAT aircraft will be made out of composite materials which help to lighten the airframe. Due to this new technology, the environmental control of the cabin is slightly different than comparable aluminum aircraft in the past. The cabin pressure will be equivalent to 6,000 feet rather than the traditional 8,000. This will help to reduce the stresses on the airframe as well as provide a more comfortable ride for the passengers.

A cabin temperature sensor will be located in the fuselage just above the storage compartments. The pilots will be able to monitor this reading from the cockpit and make any changes to cabin temperature to assure a comfortable flight.

The SWAT's emergency system will consist of flight crew oxygen, passenger oxygen, emergency lights, and a slide for exiting the aircraft. If the cabin pressurization in the aircraft drops below a safe level (an equivalent cabin altitude of 14,000 feet or higher) due to a system failure, compartments containing oxygen masks will automatically (or when switched on from the aft overhead panel) open above the passenger and crew seats as well as in the lavatories. Passenger oxygen masks are supplied by two oxygen bottles in the forward hold and will not flow until the mask is pulled by the passenger. The bottle capacity will be 76.5 cu ft each and the bottle pressure is indicated on the aft overhead panel. Each passenger mask will supply 12 minutes of oxygen based on the following emergency flight maneuver estimations:

- 0.3 minute delay at 37,000 ft.

- 3.1 minute decent to 14,000 ft.

- 7.6 minute hold at 14,000 ft.

- 1.0 minute decent to 10,000 ft.

Crew oxygen is stored in a single bottle in the forward hold and the masks are deployed under the same conditions as the passenger oxygen masks. The flight crew will be able to regulate the flow in their masks for three different situations: a normal air/oxygen mix used is no flames are present, 100% oxygen used if smoke or flames are present, and an emergency setting used which supplies 100% pressurized oxygen to clear mask and goggles of fumes (this setting will also be used is depressurization occurs above 39,000 ft.

In the event of a main power outage, emergency exit lights can be switched on from the cockpit as well as the flight attendant panel. The lights are powered by their own Ni-CAD batteries and will only last 10 minutes. [7]

9.8 Fire Prevention and Control

Fire detections and prevention is, of course, an important step in insuring the safety of a commercial aircraft such as the SWAT. This system will be similar to that of the 737 series. Each engine will have two fire detection loops for redundancy; in the event that both loops were to fail, the pilots will be notified by a light on the fire protection panel in the cockpit. These loops will be able to detect an overheating as well as a fire. If a situation is detected, the pilots can pull a switch on the protection panel and extinguish the fire. The APU will also be equipped with a similar detection and extinguishing system along with the lavatories, cargo compartment, and cockpit panel. There will be fire extinguishers located in the forward and aft crew stations as well as the cockpit. The cargo hold will also store a fire extinguisher as well as the ability to lower its cabin pressure in order to prevent smoke from penetrating the passenger areas. [7]

9.9 Lighting System

All of the lighting on the SWAT aircraft will meet the requirements of the FAA and the FAR 25. Honeywell's new Astreon series of high performance solid state lighting products will be used for all exterior lighting. This new system is composed of LEDs (Light Emitting Diodes) which offer a longer lifespan, and therefore lower costs, then their predecessors such as halogen or incandescent lights. The lighting system will include lights in all of the mandated areas such as strobe, navigation, anti-collision, landing, taxi, as well as logo lights. [12]

9.10 Water, Galley and Lavatory System

The SWAT will contain a 40 US gallon water tank (much like the 737-400) located behind the aft cargo hold. This tank will provide usable water for the galley and lavatory sinks; the lavatory bathrooms will use chemicals so there is no need for water. All water is sanitized and flushed regularly to meet regulations as well as pressurized in the tanks for circulation throughout the aircraft.

The galleys and lavatories will both be furnished by one of the aerospace industries leading aircraft interior companies; JAMCO. These areas will not only be increasingly functional, but aesthetically pleasing, helping to innovate and differentiate the SWAT aircraft for the near future. The aircraft will be equipped with a galley in the forward section as well as the aft section of the fuselage. Each galley is equipped with JAMCO's newest line of durable, low weight inserts including a steam oven, small sink, microwave oven, as well as an air chiller.

Multiple jump seats will be available for crew members along with lock to keep beverage and food carts in place.

The SWAT will also feature two lavatories in the forward and aft sections of the fuselage. Also designed by JAMCO, these lavatories will have a similar layout to that of a 737. Amenities will include infrared faucets and soap dispensers, small counter and mirror, and a small storable changing table. Each of these lavatories is vacuum flush meaning that they can virtually be placed anywhere on the aircraft; this will prove useful for different SWAT seating layouts that may follow the original. [13]

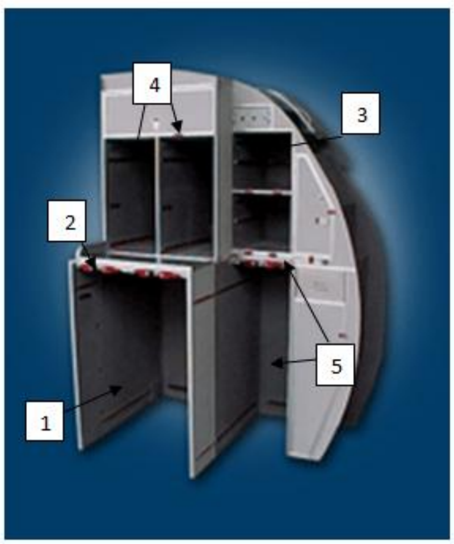


Figure 9.6 – Galley Layout

1	Service Cart Compartment
2	Cart Lock Mechanism
3	Microwave Compartment
4	Food Storage
5	Miscellaneous Storage

http://www.airoindustries.com/images/pics/B737Galley.gif

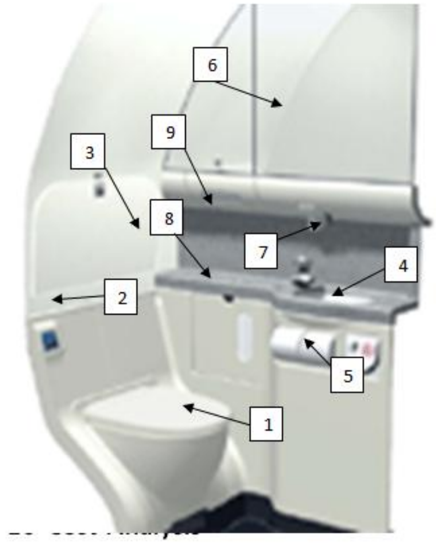


Figure 9.7 – Lavatory Layout

1	Toilet
2	Flushing Mechanism
3	Foldable Changing Table
4	Faucet and Sink
5	Toilet Paper Rack
6	Mirror
7	Soap Dispenser
8	Garbage Compartment
9	Paper Towel Dispenser

http://www.boeing.com/news/releases/2004/photorelease/q1/040116g.gif

10 Cost Analysis

Cost is always an important factor to consider when designing and manufacturing anything. Cost estimating methods, were used to predict the cost for the different elements of the total life-cycle cost.[1]

10.1 Research, Development, Test and Evaluation

Research, development, test, and evaluation, also known as RDT&E, includes all the costs for design engineering, all the testing involved, as well as technology research. It basically covers all the costs that are necessary in the aircraft conceptual design part of the project. Since, numerous hours are spent in RDT&E, the labor costs are calculated by multiplying the estimated number of hours spent, by the “wrap rate” of the field the work was performed in. The wrap rate covers the salary of the employee, fringe benefits, and overhead. These wrap rates were adjusted for 2010 for each of the various fields and are listed in Table 10.1.

Table 10.1 - Average wrap rates

Field	Hourly wrap rate
Engineering	$111.80
Tooling	$114.40
Quality Control	$105.30
Manufacturing	$94.30

.

The number of hours spent working in these four fields were estimated using equations from Raymers aircraft design book.[1] The hours spent working on each of the various fields are shown in Table 10.2.

Table 10.2 - Estimated number of hours worked

Field	Number of Hours Worked
Engineering	16,665,730
Tooling	11,295,082
Manufacturing	63,248,401
Quality Control	4,806,878

In addition to the labor costs, there are costs for development support, flight tests, manufacturing materials, and engineering production. All of these costs are included in the RDT&E costs. An additional cost included in the civil purchase price is the flyaway cost. This includes production of the airframe, engine, and avionics. The total cost for RDT&E, and production needs an additional cost of $2,500 per passenger to cover the cost of seats, luggage bins, lavatories, and similar objects. The costs for 500 aircraft for RDT&E and flyaway are located in Table 10.3.

Table 10.3 - Costs for RDT&E for 500 aircraft

	Cost
RDT&E	$9,663 million
RDT&E+flyaway	$12,078 million
Additional Costs	$219 million
Total Civil Purchase Price per Aircraft	$24.6 million

10.2 Operation Costs

There are also operation and maintenance costs to consider. Using an estimated value of 3500 flight hours per aircraft per year, the operation and maintenance costs for 500 aircraft over 30 years are located in Table 10.4.

Table 10.4 - Operation and Maintenance Costs for 500 Aircraft for 30 Year Run

	Cost
Crew	$42.3 billion
Fuel	$67.0 billion
Maintenance	$44.1 billion
Depreciation	$21.1 billion
Insurance	$1.8 billion
Total O&M Cost	$176.2 billion

The trend is that the total cost increases as the weight of the aircraft increases. Since this aircraft is a strut based aircraft, the result is that the overall costs will be lower than a non strut based type.

11 Conclusion

The 2009-2010 American Institute of Aeronautics and Astronautics Foundation Team Aircraft Design Competition presented Slipstream Aerospace with a request to design a 175 passenger commercial airliner that could use biofuels as well as having a 25 percent increase in the maximum lift to drag ratio from the Boeing 737-800 series. Additionally it would have to be ready for production in 2010 which only allowed the use of currently being researched and implemented upcoming technologies and improvements. Slipstream Aerospace has accepted this request and thereby proposes the SWAT design as not only meeting but exceeding all the technical requirements set forth in the request for proposal. Table 11.1 shows the technical specifications of the RFP as well as the SWAT response.

Table 11.1 – RFP technical requirements and response

Criterion	RFP requirement	SWAT capability	Compliance
Passengers	175 (1 class)	177 (1 class)	Yes
Max L/D	>= 125%	146.3%	Yes
Fuel	Utilizes Biofuels	Utilizes Biofuels	Yes
Balanced Field Length	< 8200 feet	7300 feet	Yes
Maximum Cruise Range	>= 3500 nm	3850 nm	Yes
Storage Area	1240 ft^3	1290 ft^3	Yes

References

[1] Raymer, Daniel P. *Aircraft Design: A Conceptual* Approach. 4th ed. Reston, VA: American Institute of Aeronautics and Astronautics, 2006.

[2] “CFM: The Power of Flight.” <http://www.cfm56.com/products/cfm56-7b/cfm56-7b-technology>.

[3] “Blended Wing Body.” Wikipedia, The Free Encyclopedia. 17 Nov 2009, 04:19 UTC. 10 Dec 2009 <http://en.wikipedia.org/w/index.php?title=Blended_wing_body&oldid=326291039>.

[4] “Tip Stall Effects.” http://www.tpub.com/content/aviation2/P-1231/P-12310054.htm.

[5] “Wing loading.” Wikipedia, The Free Encyclopedia. 6 Dec 2009, 12:47 UTC. 10 Dec 2009 <http://en.wikipedia.org/w/index.php?title=Wing_loading&oldid=330053783>.

[6] “Aircraft flight control system.” Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 30 Apr. 2010. Web. 3 May. 2010.

[7] Brady, Chris. “The Boeing 737 Technical Site.” 1999. http://www.b737.org.uk/

[8] “Auxiliary power unit.” Wikipedia, The Free Encyclopedia, 1 May. 2010. Web. 3 May. 2010.

[9] “Primus Epic Intergated Avionics System.” Honeywell International Inc. 2010. http://www.honeywell.com/sites/aero/PrimusEpic.htm

[10] “AKH Containter.” VRR Air Cargo Equipment. 2010. http://www.vrr-aviation.com/products/AIR-CARGO-CONTAINERS/akh-container

[11] “787 Integrates New Comp0site Wing De-Icing System.” Composites World. 2009. http://www.compositesworld.com/articles/787-integrates-new-composite-wing-deicing-system

[12] “Honeywell Aerospace: Exterior Aircraft Lighting.” Honeywell International. 2010. http://www.honeywell.com/sites/aero/Aircraft_Lighting3_C3B8B3C2A-554A-D1A0-67E4-5EE3C63767BA_H00119971-50AA-125A-6492-2483986B0536.htm

[13] “JAMCO Aircraft Interiors.” JAMCO Corporation. 2009. http://www.jamco.co.jp/e/e-interiors/interiors-index.html

[14] Grasmeyer, Joel. Stability and Control Derivative Estimation and Engine-Out Analysis. 1998, January. Aerospace and Ocean Engineering Department, Virginia Tech. Blacksburg, VA.

[15] “LDstab sizing program.” 20 February 2009 < http://www.aoe.vt.edu/~mason /Mason_f/MRsoft.html#Nicolai>.

[16] Etkin, Bernard; Reid, Lloyd. *Dynamics of Flight Stability and Control*. 3rd edition. University of Toronto. John Wiley & Sons, Inc. 1996.

[17] Norris, Guy. *Exploiting eCore*.

[18] “Krueger flaps.” Wikipedia, The Free Encyclopedia. 16 February, 2009. http://upload.wikimedia.org/wikipedia/commons/6/68/Krueger-Flap.png

[19] The Seattle Times. [Online] August 30, 2007. [Cited: December 10, 2009.] http://seattletimes.nwsource.com/html/boeingaerospace/2003858756_boeingenergy30.html.

[20] Bio Synthetic Paraffinic Kerosene (Bio-SPK) OK as Jet Fuel. s.l. : Boeing, 2009.

[21] “Air NZ sees biofuel salvation in jatropha.” CarbonPositive. [Online] June 8, 2008. [Cited: 11 19, 2009.] http://www.carbonpositive.net/viewarticle.aspx?articleID=1114.

[22] “Ethanol-powered Plane Is Just One Item on Brazil Embraer's Green Push.” *Brazil Mag.* [Online] November 2, 2007. [Cited: September 10, 2009.] http://www.brazzilmag.com/content/view/8821/54/.

[23] “PetroSun Drilling Forms Algae BioFuels Subsidiary.” *Green Car Congress.* [Online] June 22, 2006. [Cited: November 5, 2009.] http://www.greencarcongress.com/2006/06/petrosun_drilli.html.

[24] “Airbus Completes First Civil Aircraft Test Flight With Alternative Fuel.” environmental LEADER. [Online] February 3, 2008. [Cited: September 10, 2009.] http://www.environmentalleader.com/2008/02/03/airbus-completes-first-civil-aircraft-test-flight-with-alternative-fuel/.

[25] “Chevron Products: Browse Mr. Gasoline Topics.” *Chevron Products Homepage.* [Online] Chevron. [Cited: December 10, 2009.] http://www.chevron.com/products/ourfuels/mrgas/browsetopics.aspx.

[26] *Military Specification MIL-A-8861B(AS), Airplane Strength and Rigidity - Flight Loads.* s.l. : Naval Air Systems Command, 1986.

[27] “Alternative Jet Fuel Reduces Aircraft Engine Emissions.” *WRIGHT-PATTERSON AIR FORCE BASE.* [Online] February 8, 2007. [Cited: September 10, 2009.] http://www.wpafb.af.mil/news/story.asp?id=123040425.

[28] “Landing Gear.” The Boeing 737 Technical Site. www.b737.org.uk/landinggear.htm

[29] “AKH Container.” VRR: Air Cargo Equipment. 2010. http://www.vrr-aviation.com/products/AIR-CARGO-CONTAINERS/akh-container

[30] “737-NG Flightdeck.” The Boeing 737 Technical Site. http://www.b737.org.uk/flightdeck737ng.htm

[31] “Tip Stall Effects.” Integrated Publishing. http://www.tpub.com/content/aviation2/P-1231/P-12310054.htm